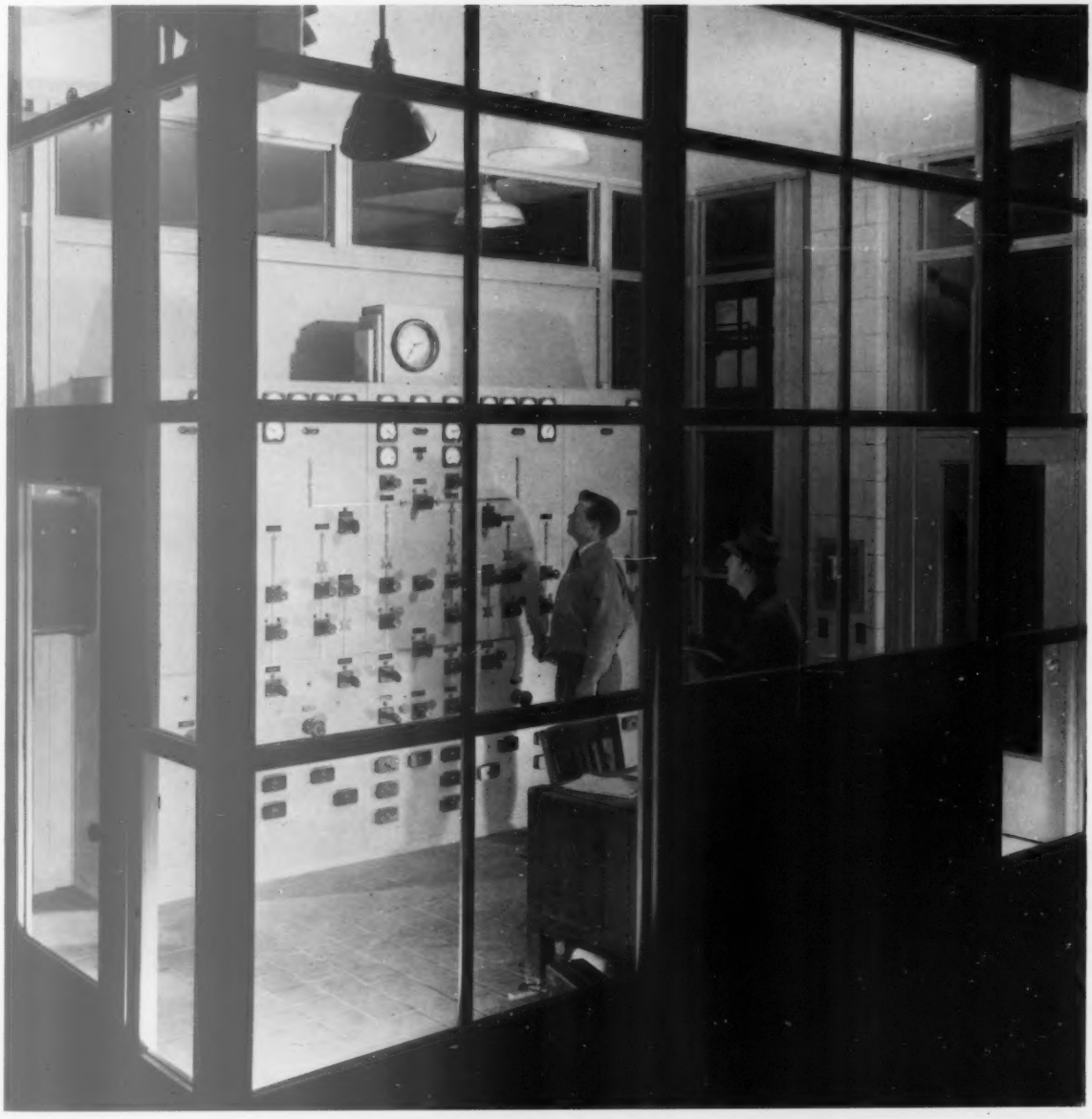
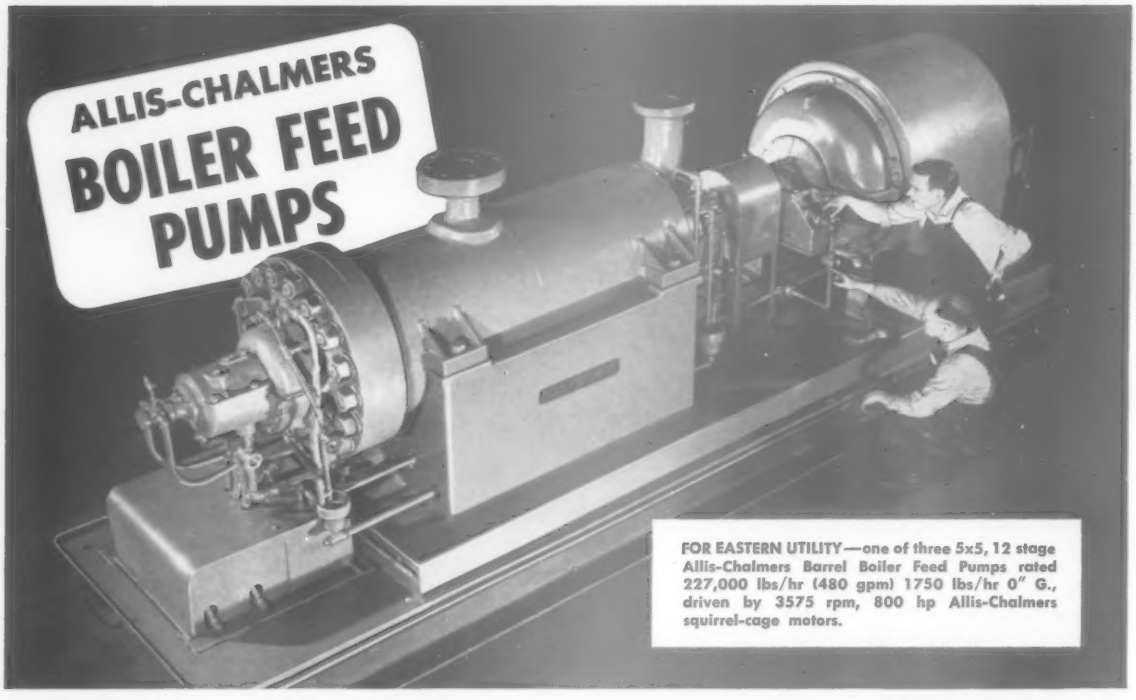
ALLIS-CHALMERS Electrical REVIEW



Second Quarter, 1950

A Single Responsibility for Pumping Performance!



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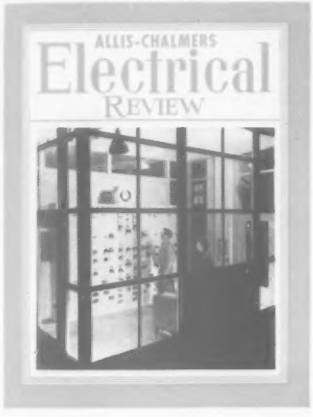

AT DETROIT'S BLUE HILL Pumping Station this 5-panel enclosed control board handles four 2,000-hp synchronous motors and two 200-hp motors for pump drive. Motors start under full voltage.

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Allis-Chalmers

Electrical Review

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ALLIS-CHALMERS Electrical REVIEW

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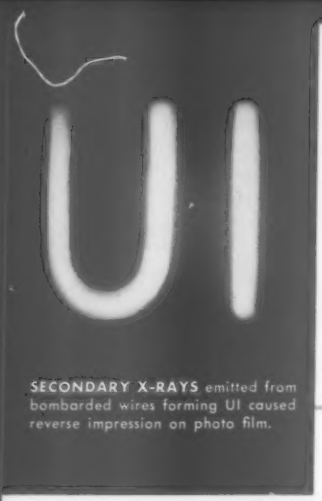

SECONDARY X-RAYS emitted from bombarded wires forming UI caused reverse impression on photo film.

Building the 300,000,000 VOLT BETATRON

by

BEN F. UREDA
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and
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Building the world's largest and most powerful betatron—told by engineers who supervised its construction.

UNLIKE VAN LEEUWENHOEK, who learned so much about the unknown world with the aid of his hand-made glass bead microscope, today's scientists need tremendously larger and infinitely more powerful instruments to delve further into the recently unveiled secrets of the atom.

One of the most spectacular of these powerful instruments is the 400-ton, 300 million-volt betatron which was recently placed in operation at the University of Illinois. Designed by the inventor of the betatron, Professor Donald W. Kerst, Ph. D., the unit is now being used in the new Physics Research Laboratory under the supervision of Dr. Kerst and his staff.

Building of the giant machine is an excellent example of teamwork between research scientists and design engineers, and of cooperation between a university and heavy industry. Dr. Kerst and his associates provided the theoretical background and did all of the preliminary design and calculation work. Details of the core and coil structures, and methods of assembly as well as the erection itself fell to industry. This coordination of knowledge and effort between the university and erection engineers was reflected in all stages of construction. Its contribution to solving the thousand and one problems involved in designing and assembling the world's biggest transformer core makes an interesting story.

Rich yield during first trial

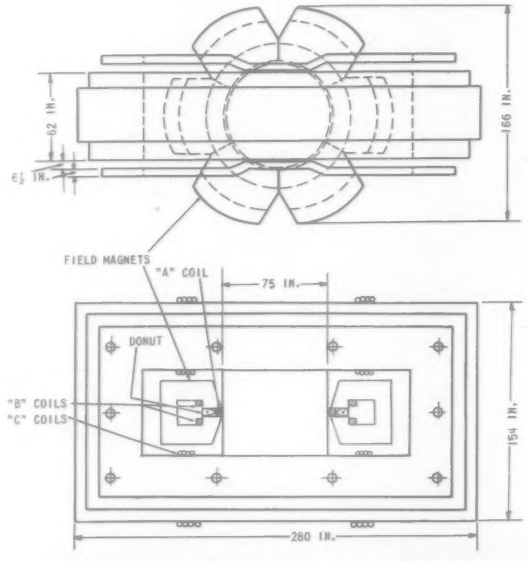
Amazingly, the betatron produced X-rays on its first trial on February 15, 1950, and was brought up to its full energy of 340,000,000 volts in less than two weeks. Also highly significant was its immense yield of X-rays: more than 250 roentgen units per minute at one meter from the target. Although this yield is many times that of any other high voltage accelerating machine, this figure is far below the yield which can be expected after more stable operation and after trimming and adjustments have been completed. Mesons, which are little known sub-atomic particles, have been produced. Their characteristics will be studied through microscopic examination of photo exposures and direct observation of "cloud chamber" photographs.

The betatron derives its name from "beta," symbol for high energy electrons, and "tron," meaning "an instrument for"; hence an instrument for producing high energy electrons.

Development background for the 300 MEV betatron dates back to 1940 when the first perfected betatron produced X-rays with 2,300,000 volts energy. Shortly afterwards Dr. Kerst's idea was developed into the 22,000,000-volt betatron with push-button control, now commercially available for cancer therapy and industrial radiography. These improved machines are capable of making detailed radiographs through 20 inches of steel in 20 minutes.

The 300-MEV betatron will be used largely to study the meson, which can be produced only with accelerating machines having energies in the range of cosmic ray phenomena, i.e., greater than 100,000,000 electron volts. An 80,000,000-volt model built and operated in 1947 by the University of

(Continued on Page 6)



TOP AND FRONT VIEWS of magnetic structure shows the dimensions and arrangement of the principal betatron components. **(FIGURE 1)**

COMPLETED 300-MEV BETATRON is already in use helping to compile the great mass of data needed to expose the secrets of the meson, the recently discovered subatomic particle whose characteristics remain unknown. Rear view shows orbit positioning transformer on top.

Here's How It Works —

OPERATION OF THE BETATRON simulates that of an alternating-current transformer, the secondary winding of which has a very large number of turns. It is evident that the voltage in such a winding would increase with the number of turns. Each electron which makes a trip around the core of the magnet will have gained an increment of energy in electron volts equivalent to one turn of the secondary of the transformer. The primary windings, called the "C" coils, are placed on the outer legs of the magnetic yoke as shown in Figure 1 in the text. Now we will replace the copper wire secondary winding with, in this case, a doughnut-shaped vacuum tube, which encompasses the central leg of the magnet.

Now let us take an electron and inject it at some initial velocity into the vacuum tube. By known physical laws, the electron will be accelerated by the changing flux in the main core, and will tend to move at right angles to the flux. If the path of this electron is to be kept in a circular orbit, it must be restrained both radially and axially by an outside force. This force is produced by six field magnets, the pole faces of which are shaped to focus the electron, or beam of electrons, into a sharply defined orbit. The windings for these magnets are called "A" and "B" coils.

It will be noted from the schematic diagram, Figure A, that the current in the "C" coils may be varied by means of taps on the "orbit-positioning transformer." This adjustment affords the relationship between the orbit restraining flux produced by the "A" and "B" coils and the accelerating force at the electron orbit which is necessary to confine the orbit to a limited radius.

After the electrons have been injected and accelerated to the desired energy, the orbital radius must be expanded so that the particles strike a metal target which then emits X-rays. As seen in Figure 1, two portions of the central core (called "side packages") are separated from the rest of the magnet so that they may be separately wound. These side packages are not magnetized by current through the "C" coils. Orbit expansion is accomplished at the end of the acceleration period by suddenly increasing the flux in the core without increasing the field at the orbit, i.e., by sending a pulse of current from a separate synchronized source through the side package or "expander" windings and thus increasing the flux in the core by nine or ten percent.

A new principle of biasing is used to get nearly double voltage from a given betatron size. Distributed windings are placed at points around the magnet, their position and number determined by the amount of leakage flux in any given part of the magnet. About 1,000 amperes d-c is passed through these parallel windings so as to bias the core to approximately minus 14,000 gauss. The current pulse through the "C" windings is large enough to effect a flux density swing from minus 14,000 to plus 16,000 gauss, i.e., a flux density change of

Facts and Figures about the U of I 300-Mev Betatron

1. Betatron weighs approximately 450 tons, is 10 feet thick, 16 feet high and 25 feet long. Made of 70,000 laminations, the main magnet core weighs approximately 275 tons.
2. Porcelain vacuum tube enclosing electron orbit is a toroid with 104-inch outside diameter, 80-inch inside diameter and 6-inch thickness
3. Nearly 150 kw is required to run the betatron at full output.
4. Injector voltage is from 100 to 150 kv.
5. Flux density change in main magnet is 30,000 gauss in .004 sec.
6. Construction took 15 months for engineers and 11 months for erection crew. Project cost about $700,000.
7. Latest betatron yield recorded is 1,600 roentgen units per minute at one meter from the origin. (Allowable absorption by the human body is considered 0.3 roentgen units per week.
8. Betatron requires more core steel than equivalent voltage synchrotron, but has simpler control and timing circuits, and is more adjustable in operation. It can also accelerate protons.
9. Betatron operates six times per second by discharge of condensers (10,000 microfarads at 5,300 volts) through the windings. Peak current during sinusoidal discharge pulse is 21,000 amperes.
10. The main magnet would accommodate the standard steel requirements for an oil-immersed, single-phase transformer rated approximately 1,000,000 *KVA !*
11. A 20-foot thick earth and concrete wall separates betatron room from other parts of the laboratory.

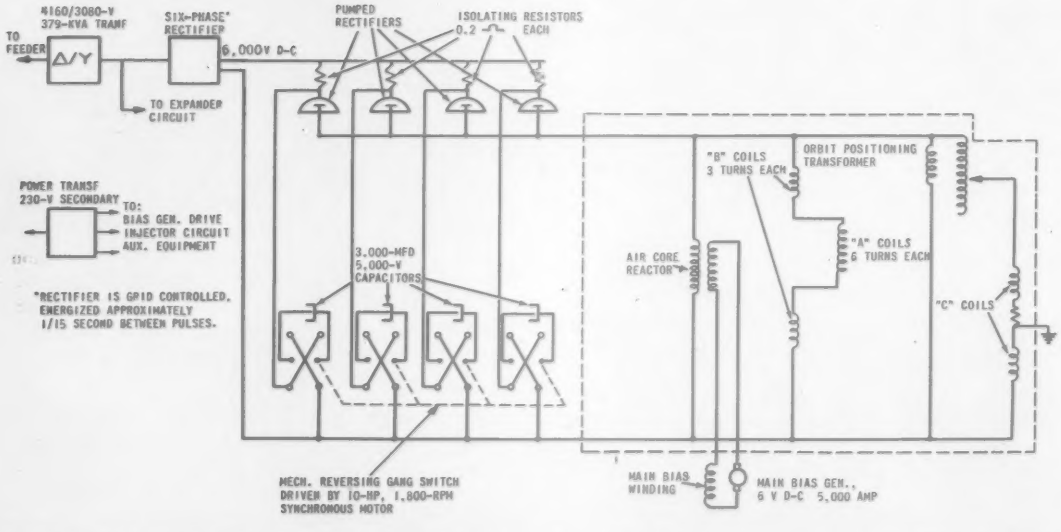
MAIN MAGNET CORE was so large that single lamination sheets could not be obtained. Two butt-jointed sheets had to be used. Angle uprights served as stacking guides. Circular object is the "A" coil. **(FIGURE 2)**

(Continued from Page 4)

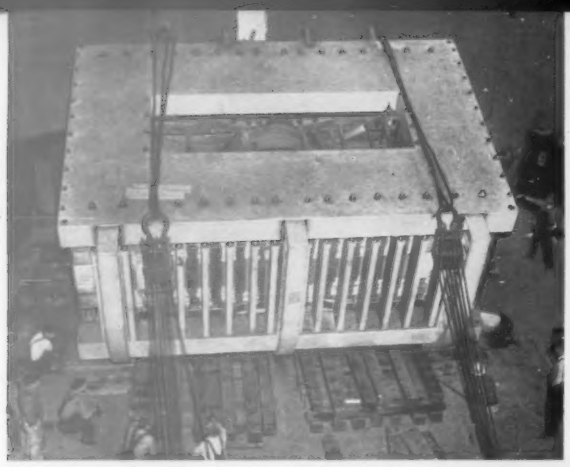
Illinois was a contributory factor to the building of the 300,000,000-volt unit. The successful operation of the model betatron according to plan spurred the construction of the larger machine.

The main magnet is the largest of its kind in the world. Weighing about 275 tons, it comprises the bulk of the weight and also determines the overall dimensions of the machine. Its shape resembles an ordinary shell type transformer core. Ventilation is provided in the central circular leg by a half-inch vertical slot through the center.

The expansion "side packages" comprise about nine percent of the iron in the central leg. Figure 1 (top view) shows that, from the central leg the "side package" iron curves outward and is separated from iron in the outer yoke by 6½ inches of maple blocking, which has adequate spacing so that the side packages and main core may be wound individually.



POWER SUPPLY and main discharge circuit for the 300,000,000-volt betatron are shown schematically. Current discharge to betatron (within dotted enclosure) is sinusoidal, lasts about 1/120 of a second, and reaches a peak of about 21,000 amp. The air core reactor isolates bias generator from high induced voltages in the main bias windings. Taps in orbit positioning transformer adjust current in "C" coils. **(FIGURE A)**



TURNING OF THE BETATRON took only one hour after rigging was completed. Power winches working in opposite directions and rockers with the proper center of curvature provided required control. **(FIGURE 3)**

ONE FIELD PIECE, or "C," required 802 different groups of iron, totalling 7,500 laminations. "C's" were clamped together with stainless steel bolts between one-inch stainless steel end clamps. **(FIGURE 4)**

In the area where the separation between the central leg iron and outer yoke iron in the side packages occurs, it was necessary to stack the laminations on a curved surface, giving a 6½-inch offset to each lamination in about 20 inches. Because of the resilience of the laminations this offset presented the problem of keeping the butt joints closed. Best results were obtained by placing one weight on the central core portion and another on the outer yoke portion of each curved lamination. Stacking was not easy, since there were four such laminations on each layer and one end of each lamination had to be held in place while the next was laid over it.

Core assembly required ingenuity and skill

Placing the laminations in their first and final position and ensuring a close butt joint required more than the normal care used in stacking a transformer core.

The overall job of stacking the magnet was very satisfactory as evidenced by the fact that the magnetizing current was comparable to that obtained on the manufacturer's assembly floor. Figure 2 is a view of the beginning stages of stacking the main magnet.

Since the final pressure applied to the laminations came from the tension in the bolts along the outer edge of the clamps, or end frames, and uniform pressure over the laminations was desired, a system using jacking bolts was used. These acted as a third-class lever wherein the force applied was the tension of the bolts, the jacking screws the fulcrum, and the work done was at the laminations. Proper pressure applied to the laminations was determined by measuring the elongation of each of the bolts with a strain gauge.

The end clamp assembly was made at the laboratory and the parts were welded together. Factory-trained welders ex-

30,000 gauss. The side packages are biased separately in the same manner and to the same degree of saturation as the main core.

High voltage induced in the main magnet bias windings by the flux produced by the "C" windings is bucked out by a huge choke coil (illustrated in the schematic diagram) to protect the low voltage bias generator.

The machine operates six times per second, and its sound due to magnetostriction of the laminations is strangely like that of chopping a large timber with an axe. During each pulse, the "A," "B," and "C" coils are energized by discharging a bank of condensers (10,000 microfarads at 5,300 volts) through the windings. Four large pumped rectifiers in parallel are placed in series with the condensers and are the means of timing the discharge. Surging through the coils is a peak current of 21,000 amperes (18,000 through the "A" and "B" coils and 3,000 through the "C" coils). The L-C combination of the main discharge circuit has a resonant frequency of about 60 cycles while the expander pulse is about 180 cycles per second. Injection of the electrons occurs early in the discharge, and expansion of the electron orbit is initiated so as to strike the target at about 75 degrees after the beginning of the pulse.

The power supply is a six-phase rectifier. Its function is to restore to the condenser bank the decrement of voltage lost during each betatron pulse (about 300 volts).

The inner surface of the half-inch thick porcelain wall of the doughnut (Figure 6 in the text) is coated with a thin layer of palladium which drains off any charge that might accumulate on the wall. The electron injector, which protrudes inside the doughnut through a sealed glass aperture, operates much like other electron guns, and uses a square wave pulse of about 100-kv amplitude and two microseconds length. Average electron emission during this injection period is about 2.5 amperes.

Overload relays, thermostats, interlocks and similar devices protect the power supplies and control circuit. Explosion boxes are novel protective devices employed to cut power to the betatron quickly in case of an arcback in one of the main discharge circuit ignitions. In case of an arcback (or an unwanted stray signal) about four feet of primacord explosive is detonated (making enough noise to send uninformed visitors scrambling out of the room). What happens is this:

A signal from a biased pulse transformer, located on the anode lead of the ignitron, is amplified and sent to a detonating circuit. The primacord fits into the inner of two coaxial copper cylinders which are connected to opposite sides of the condenser bank and are separated by a thin tube of plastic insulation sufficient to withstand the full condenser voltage. The explosion (inside a steel box) breaks the insulation between the cylinders and the energy stored in the condensers is thus completely dissipated in the replaceable short cylinders in 400 micro-seconds.

LEVEL READINGS in the gaps of the "C's" were taken while field pieces were aligned on the laboratory floor. In final installation, gap dimensions have to be uniform to prevent distortion of orbit field. **(FIGURE 5)**

DOUGHNUT-SHAPED VACUUM TUBE, heart of the betatron, is shown being inspected by Dr. G. D. Adams, its designer. Electron acceleration within its confines approximates the speed of light. **(FIGURE 6)**

perienced in handling jobs of this size held the surface adjacent to the laminations flat to within ⅛ of an inch as specified.

Laminations were stacked flat, as in a transformer. Again as in a transformer, laminations are standing on their edge in the final position. To turn the pile of laminated iron through 90 degrees is ordinarily a minor detail where cranes of suitable capacity are available. However, the completed magnet and end frames of this machine weighed 350 tons and no cranes were available; therefore, the turning operation required major consideration.

Three rockers were welded to the end frames. The center of curvature of these rockers was placed at the center of gravity just as in a wheel. The turning then was simply a matter of rolling rather than lifting. The radius of curvature of the rockers was 117 inches. These rockers are still attached to the machine except for a section of the center cradle which was made removable. Base blocks, which also keep the machine from rolling back, support the weight of the betatron.

Turning from the stacking position to the final position involved a considerable rigging problem. All rigging was attached to lugs cut from a 4-inch plate and welded to the end frame. Figure 3 shows the arrangement of blocks and cables turning the machine over. Two power winches did the actual work; one winch pulled forward and the other, located outside the building, held back. The pulling winch was easily braced against the building but the holding winch required a "dead man" to anchor it. The "dead man" consisted of twenty 30-foot long by 12-inch square cross section timbers buried ten feet in the earth. The turning operation took only one hour after the rigging was completed.

Magnet assembled sectionally

The main magnet and field pieces were stacked simultaneously. The design and construction of these field pieces was the most critical part of the whole project.

The orbit restraining magnet in the lower energy betatrons is a part of the center core of the main magnet. In the 300-MEV betatron the two pole faces of this orbit-restraining magnet are built in six separate sectors. Each sector is a block of laminated iron, roughly a "four foot cube" weighing 11½ tons. General specifications of one field piece were 7,500 laminations in 800 different groups, held together by straight bolts and stacked to give a circular pole face and resisting a magnetic squeeze of 20 tons.

Stacking the .014-inch laminations (Figure 4) to a curved pole face and then clamping them together with straight bolts meant that, at every quarter-inch of stack height, the location of bolt holes was changed. The sheets of iron were stamped out, each group requiring a new setting of dies.

To get a circle of field pieces, the junction of two "C's" (a side view of field pieces is like the letter "C") must be a radial line which makes an angle of 60 degrees with the plane of the back portions of the laminations. To get this angle, clipped laminations were stacked throughout the "C" and the laminations were bent to obtain the curvature. This gave a uniform distribution of the clipped laminations, and in the "C" uniformity was of prime importance. As in the main magnet, insulating paper .005 inch thick was stacked into the "C" every one-quarter of an inch.

A stacking fixture, or jig, gave the starting angle and held the 6-inch gap opening to within a few thousandths of an inch. The first field piece had numerous starts and restackings before completion, but familiarity with the procedure shortened the stacking time of the later "C's" to one week per field piece.

Trouble multiplied after the completed field pieces were removed from the jig. The bottom laminations had a tendency to move away from the stacking fixture, opening the gap to more than the specified six inches. The stack of iron was spongy while stacking, and, as laminations were added, the bottom laminations were compressed, causing a movement away from the jig. After the stack of laminations was bolted together it took considerable pounding with heavy hammers to shape the "C" properly.

The amount of tension in the bolts required to make a rigid mass of the field piece was a problem solved with the aid of a torque wrench. Measuring tensions by checking elongation of the bolts was tried, but, because the bolt ends were not readily accessible, this method was abandoned.

The finished field pieces were turned to final position with a specially constructed jig. This turning operation was studied in detail because it was feared that any rough handling of the "C" would change its dimensions. The "C's" were actually very rigid pieces, as discovered later when attempts were made to correct a slight discrepancy in gap dimensions.

Assembling the "C's" around the center core was by far the most exasperating of all the operations on this project. More time and patience was spent on this phase of construction than on any other. The "C's" were first aligned on the floor of the laboratory as in Figure 5, and final checks were made of gap dimensions, curvature, and insulation. "C's" were then hoisted into position inside the window of the main magnet. The one-inch mounting plates for the field pieces were

mounted on solid bakelite cylinders 4½ inches high and 6 inches in diameter, which isolated the "C" electrically from the rest of the machine.

Two steel bands with turnbuckles at each space between "C's" were wound around the entire circle of the field pieces to pull them into position. A uniform squeeze had to be applied to obtain a true circle. Too much tension at any one space would have caused the "C" to enter in too far and collapse the circle. Moving the 70-ton circle even an eighth of an inch was no mean task.

The circle finally obtained varied from the accurate template constructed inside the gap of the "C" by 1/16 of an inch on a diameter of 90 inches. The pole face plane had a variation of .020 of an inch which is excellent alignment in view of the fact that these were not machined parts.

Coil assembly posed challenge

The "A" coil had to be wound to meet extremely exacting demands. It consisted of six turns of stranded wire with a transposition of strands made at approximately 20-inch intervals. Each strand was well insulated because nearly 100 volts appear between the strands during each pulse. The coil was insulated for 18,000 volts and rated at 20,000 amperes at six pulses per second.

This coil operates under what normally would be termed short-circuited conditions. A force of 30 tons tends to compress the coil to a smaller diameter. Its close proximity to the orbit required that the coil be uniform in construction so as to avoid undesirable magnetic effects. A slight but unobjectionable "bump" in the magnetic field was noted at the juncture of the leads and the coil.

The "A" coil was attached to the core by means of saw-tooth bakelite wedges, a bronze saw-tooth counterpart and a compression spring that automatically took up any slack in the coil. A thermosetting plastic material was applied to the iron laminations to insulate them from the bronze portion of the wedge. The "A" coil was designed to fit tightly into the gap of the "C" in the field pieces. For construction purposes the coil was collapsed 3/32 of an inch and later wedged apart to fit snugly into the gap.

Differing considerably in construction from the "A" coil, the "B" coil, made of stranded copper cable with an outside diameter of 2.6 inches, was wound into the field pieces as shown in Figure 1: three turns at the top and three at the bottom of the "C." Bakelite spacers determine the position of each turn. Stainless steel sheets with a loop extending beyond the laminations had been stacked into the field pieces. The "B" coil is tied to three such loops in every field piece. The bottom three turns were made without difficulty, but the top three required additional ties to make a solid winding that did not move when the betatron was pulsed.

An elaborate system of bias windings covers the entire main magnet and side packages. These windings were distributed so as to keep the leakage flux at a minimum by placing the ampere turns on the portion of the magnet requiring them. These points occur at all of the butt joints of the laminations. Because of the slight air gap at this point, more magnetizing current is needed to force the flux through and prevent leakage into the region outside the magnet.

The bias windings were located as soon as the main magnetic structure was turned over. About 1,000 amperes direct current was passed through a five-turn test coil encircling the central leg. This coil was suspended by ropes in order to pass through nearly the exact center of the magnet's "window." Leakage flux, and hence the position of the bias windings, was then located by means of a flux meter and a compass needle.

BETATRON INVENTOR, Dr. Donald W. Kerst, is shown operating controls which are centrally mounted for convenience. A wall, 20 feet thick, between betatron and controls gives protection against deadly radiation.

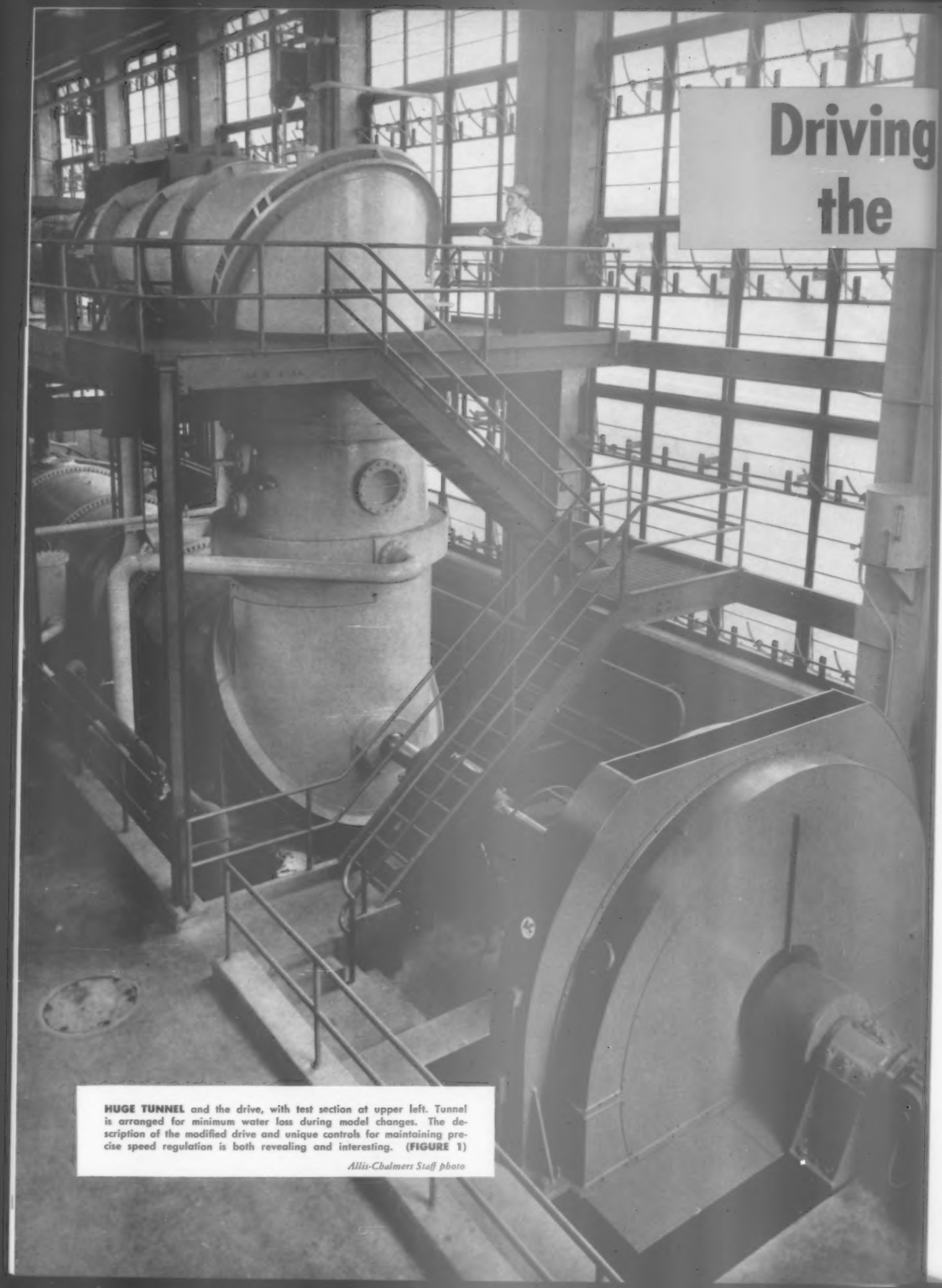
The ampere turns of the "C" windings were distributed by means of 1/16 of an inch copper shielding which covered most of the main core and side packages. This shielding also acted as a magnetic shield for leakage flux, which might distort the magnetic field at the orbit.

The betatron is cooled by a blower mounted on the floor with ductwork connecting it to the bottom of the machine. The bottom is completely enclosed, as well as the region below the "C" mounting plates. Air is forced to flow through the "A" and "B" coils in parallel paths to get to the blower. The half-inch center slot separating the main magnet core into two sections is cooled by a blower mounted in the roof of the building.

Both the top and bottom "B" coils were enclosed in insulated boxes with an air outlet constructed at every junction of two field pieces. The air will be sucked out from around the coil.

Cooling requirements have not been determined as yet but a four-hour run on the "A" and "B" coils showed an increase in temperature not approaching a critical value. It appears now that cooling may be turned on at night and only after the betatron has been operated during the day.

Driving the



HUGE TUNNEL and the drive, with test section at upper left. Tunnel is arranged for minimum water loss during model changes. The description of the modified drive and unique controls for maintaining precise speed regulation is both revealing and interesting. **(FIGURE 1)**

Allis-Chalmers Staff photo

WORLD'S LARGEST WATER TUNNEL

by

E. F. BOENING
Engineer, Control Section

F. M. SCOTT
Engineer, Motor Generator Section*
Allis-Chalmers Mfg. Co.

Modified Kraemer drive gives Penn State's new tunnel ¼ percent speed accuracy at all loads.

THE LARGEST WATER TUNNEL in the world has been undergoing preliminary tests during the past several weeks at The Pennsylvania State College Ordnance Research Laboratory. Operating under contract to the U. S. Navy Bureau of Ordnance, the Garfield Thomas Water Tunnel will serve an important function in future hydrodynamic research, providing accurate facilities for testing large scale model marine propellers, submarines, torpedoes, and other types of marine equipment.

Although there has been wide interest in wind tunnels and an appreciation of the great help they have provided in aerodynamic research, only a few water tunnels have been built and relatively little is known about them, in spite of the vast amounts of money and time and power involved in the field of marine equipment.

The tunnel,[2] shown in Figure 1, incorporates many unique features in the drive and in the control. The 95-inch, four blade, variable pitch propeller is powered by a 2,000-hp, 195-rpm, 2300-volt wound rotor motor, utilizing a modified Kraemer type of speed control. This consists of an adjustable speed motor-generator set with a 1530-kva motor and a 280-kw d-c generator, a constant speed motor-generator set consisting of a 350-hp d-c motor and a 312-kva synchronous generator, and necessary d-c and a-c control equipment.

Figure 2a is a cutaway view of the tunnel and Figure 2b shows the dimensions of the huge tunnel.

*Mr. Scott recently joined the Allis-Chalmers Mfg. Co. Chicago District Office.

[2]Engineers for the project were Jackson and Moreland, Boston. Dr. R. B. Power of the Ordnance Research Laboratory was Project Engineer for the Pennsylvania State College.

The speed and pressure of the water can be varied both by the driving motor speed and the axial flow pump's adjustable blades. The tunnel contains approximately 110,000 gallons of water which will race around the circuit at speeds up to 50 miles per hour through the working section, four feet in diameter.

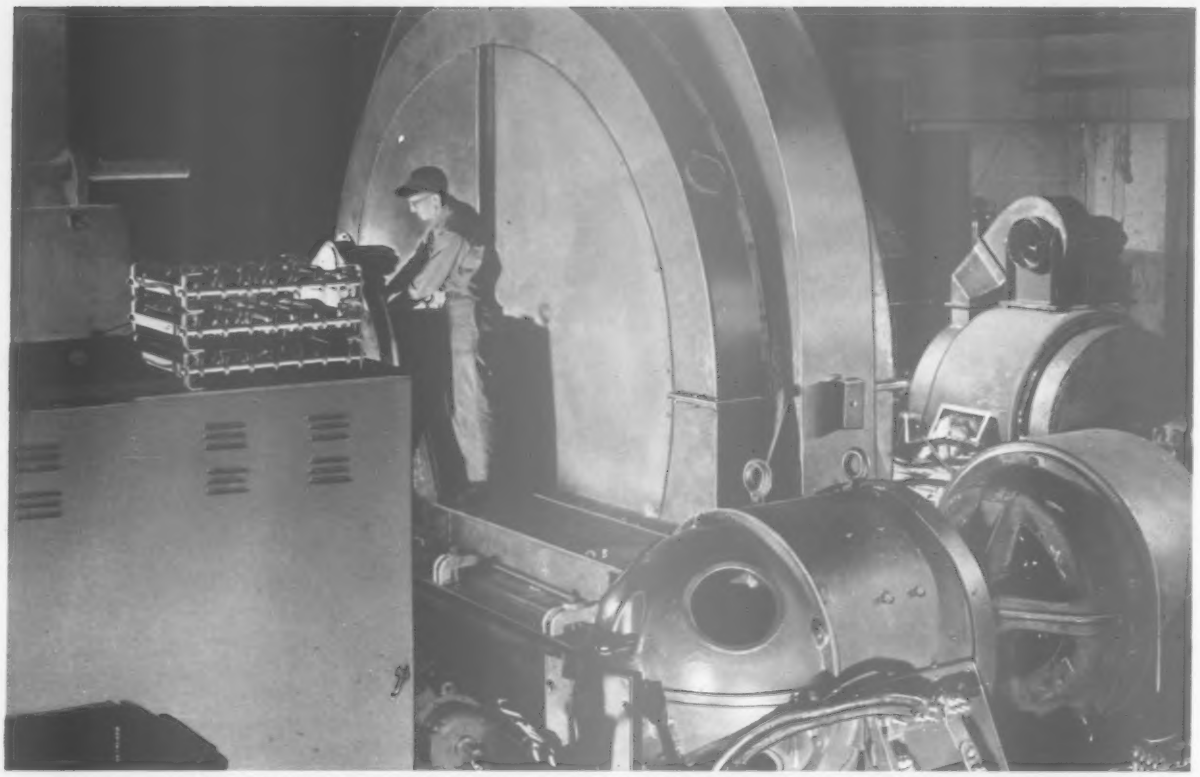
The selection of the best electrical drive for the tunnel called for a great deal of engineering investigation. The drive had to be extremely sensitive and accurate over a wide speed range, operating at lower than 40 percent of synchronous speed at 10 percent torque. The low torque and speed requirements meant that a liquid rheostat and wound rotor induction motor would not give the stable operation required. Satisfactory speed control, particularly at low speeds, was a determining factor in selecting the drive. Such a drive has the additional advantage of being able to provide variable speed with minimum sacrifice in efficiency over the speed range, as the power can be fed back into the line, whereas with the liquid rheostat or other armature resistance methods of speed control, a sizable part of the power is wasted in the form of heat. However, the main advantage of this arrangement is that in combination with a Regulex rotating regulator and electronic control it is possible to obtain very accurate and sensitive control over the wide range of speed and torque.

A diagram of the basic system is shown in Figure 3, together with machine ratings. The control equipment for the drive consists essentially of a four-panel duplex type switchboard. In this control board is housed the d-c loop breaker, the electronic equipment necessary for precision speed regulation of the drive, the automatic field application devices for the synchronous machines, the motor operated rheostat, and the necessary protective relays and indicating instruments. A feature of the drive is that all automatic speed regulating equipment can be cut out and manual speed regulation conveniently substituted.

The manual operation of the drive was considered advantageous, since inspection and maintenance of automatic speed regulating equipment can be done without materially interfering with the program of scheduled tests. The drive will not be made inoperative because of the failure of any automatic feature.

Control holds speed to within ¼ percent

During a test it is essential that the speed of the impeller be kept constant. This is accomplished by using an electronic speed regulator and a Regulex exciter to energize the field of the d-c motor, D_2, of the constant speed set. The electronic speed regulator is used to energize the control fields of the Regulex exciter.



ON TEST, drive is connected to d-c generator with resistance load. Constant speed set is in foreground.

MOTOR AND CONTROL room. Blowers provide adequate cooling of variable speed set at all speeds.

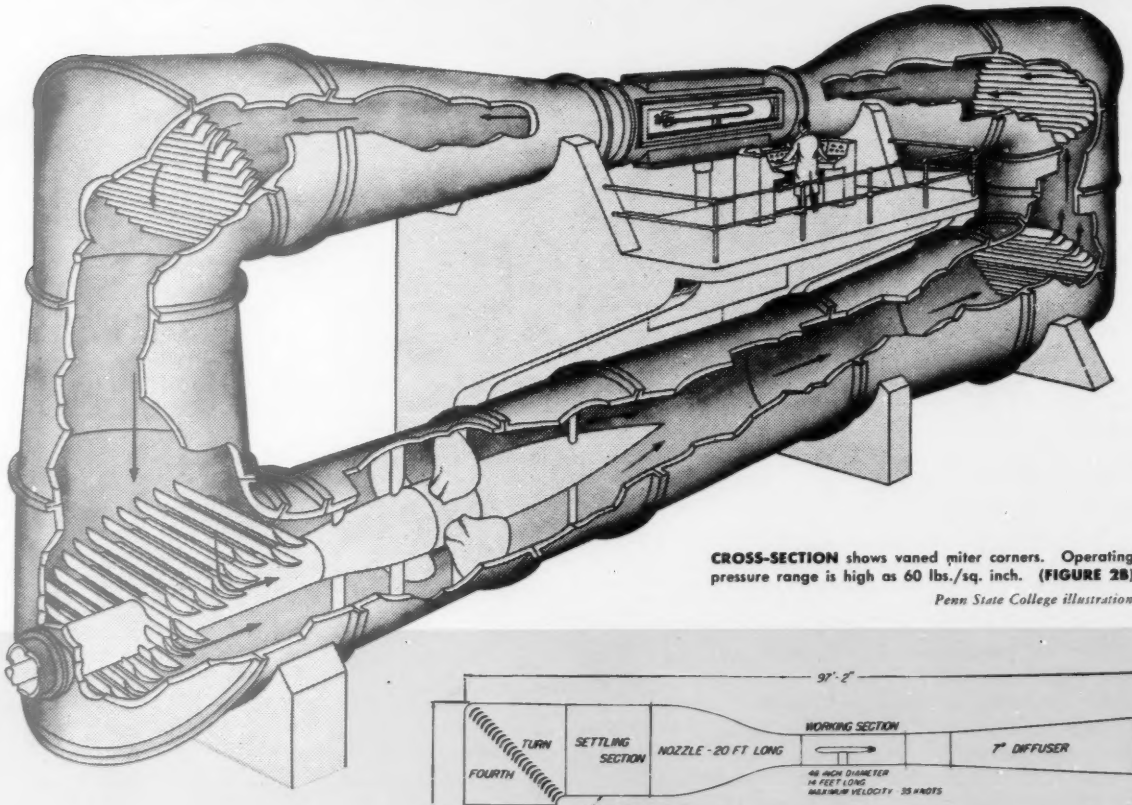
Penn State College illustration

The speed of the drive is determined by the position of the motor-operated rheostat. One ring of the rheostat, RH-B, is connected in the field of the d-c generator, D_1, of the variable speed set. The function of this rheostat ring is to set the speed of the drive to the approximate speed point. The rheostat ring, RH-A, is connected to the electronic speed regulator, which controls the excitation of the d-c motor, D_2, of the constant speed set. The electronic speed regulator for the Regulex exciter serves as the vernier speed adjustment to keep the speed of the drive constant. The speed signal is obtained from a d-c tach mounted on the variable speed set. Regulating the speed of the variable speed set is, in effect, regulating the speed of the impeller motor.

The electronic speed regulator has the following four important features:

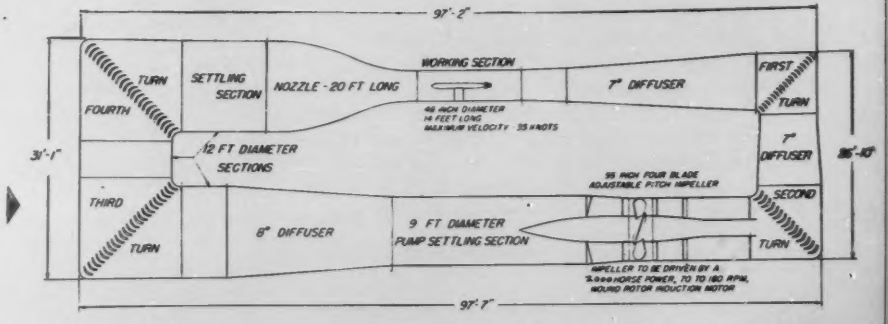
1. An electronically regulated high accuracy reference voltage which is compared to the speed signal obtained from the d-c tach connected to the variable speed set.
2. An amplifying circuit which provides the gain required by a system having an accuracy of ¼ of 1 percent speed regulation. The deviation of the speed tachometer voltage compared to the reference voltage is amplified sufficiently by the combination of electronic and Regulex amplifiers to insure large corrective action. The excitation of the d-c motor, D_2, is changed by the corrective signal in such a direction as to minimize any speed deviation.
3. An anti-hunting circuit that permits stable operation at all speeds and load conditions.
4. A current limit circuit that limits the exchange of power in the d-c loop. The current limit signal is obtained from the interpole drop of the d-c machines and is fed to the current limit tube of the electronic speed regulator. Whenever the current in the d-c loop exceeds a safe value, the current limit tube fires to reduce the acceleration of the drive and the forcing action of the electronic speed regulator.

It was necessary to exercise more than normal care in the design of the direct current machinery for this system, particularly the 280-kw, 280-rpm/1200-rpm generator. This generator operates over a speed range greater than four to one and, at times during acceleration, commutates currents as high as 200 percent. The characteristics of this generator as well as the other machines were then used to calculate the effect the various units would have on each other and on the system. For example, Figure 4 shows the calculated characteristics of the 280-kw, variable speed d-c generator expressed in terms of different load characteristics so they could be used for figuring the effect on the system as a whole. Figure 5 shows the torque and voltage calculations for various speeds and condi-



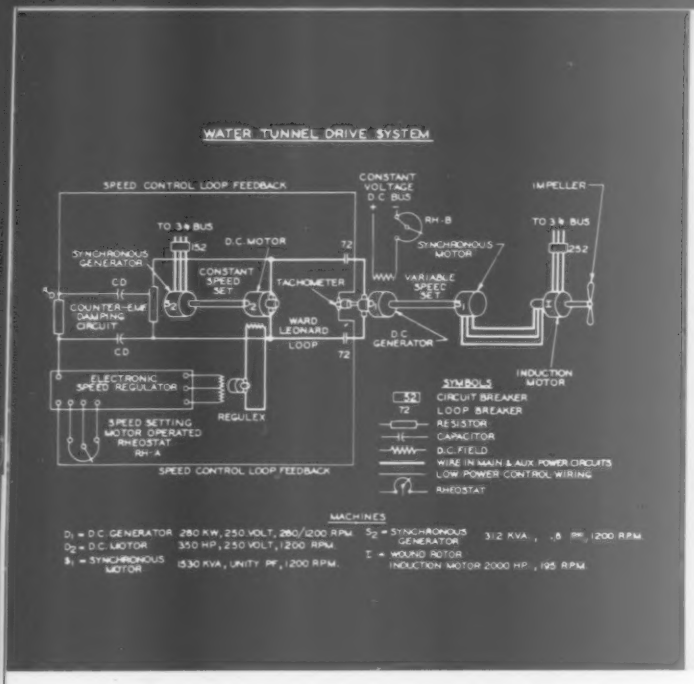
CROSS-SECTION shows vaned miter corners. Operating pressure range is high as 60 lbs./sq. inch. **(FIGURE 2B)**

Penn State College illustration

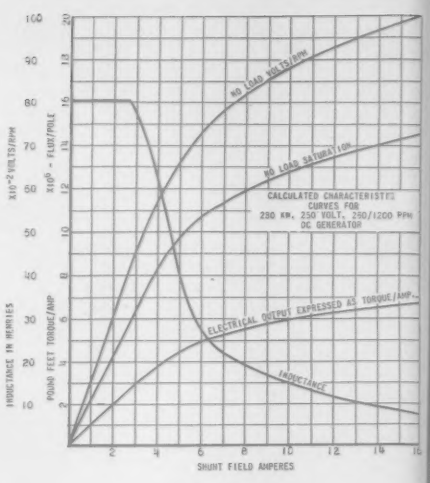


DIMENSIONS of the tunnel are shown. Refrigeration is required on some tests to cool the water. **(FIGURE 2A)**

Penn State College illustration



SIMPLIFIED diagram of drive shows function of each component. Regulex exciter gives high speed response to any changes in speed at all loads. **(FIGURE 3)**


NO LOAD VOLTS/RPM
NO LOAD SATURATION
CALCULATED CHARACTERISTIC CURVES FOR 230 KW, 250 VOLT, 290/1200 RPM DC GENERATOR
ELECTRICAL OUTPUT EXPRESSED AS TORQUE/AMP.
INDUCTANCE
INDUCTANCE IN HENRIES
POUND FEET TORQUE/AMP
SHUNT FIELD AMPERES
DC LOOP CURRENT-AMPERES

CURRENT and voltage in loop circuit at left is plotted as calculated for various speeds. **(FIG. 4)**

tions of the d-c loop circuit, based on the characteristics of the 2,000-hp wound rotor pump motor. It is interesting to note in Figure 6 how closely the test data checked the calculated values in Figure 5.

Designs had to be kept versatile enough to allow for adjustment if stability calculations, which were going on simultaneously with design work, showed the need of modification.

In one case, for example, after obtaining the characteristics of the machines and equipment to be used in the system, calculations were made to determine the oscillating characteristics of the system, depending upon the synchronous torque and damping torque of the machines involved. In this case, the calculations indicated that additional damping had to be built into the 1,530-kva synchronous motor on the variable speed set.

Of particular interest in the engineering of the water tunnel control was the study made on the analog computer at the Aerial Measurements Laboratory of Northwestern University. This study was made to predict the performance of the drive and determine the optimum damping parameters. Normally, transient performance of the drive would have been predicted by the solution of a ninth order differential equation having constant coefficients. This, however, is an extremely laborious task and often prohibitive in both time and cost. The computer saved several months of calculating time in predicting the optimum parameters of the stabilizing corrective network. Subsequent stability tests confirmed the accuracy of the predictions.

System tested under live load

The sizes of the motors and rotating equipment involved for this installation were such that it was possible to set the entire installation up on the test floor, so that complete tests could be made on the equipment under conditions which were practically the same as those of normal operation. Coupling the 2,000-hp driving motor to a large d-c generator, which in turn was connected to large banks of resistors, provided a live load, enabling tests to be made under varying loads and over a very wide range of conditions. Such an opportunity to run through complete tests is seldom possible after equipment of this size is installed, since it requires a rather large crew to operate equipment, and test schedules make it necessary to operate only at specific conditions.

The characteristic curves of the drive are shown in Figure 6. These curves are plotted from readings taken during a test run with a load on the induction motor approximating a 19-degree blade angle on the impeller.

From the curves, it is apparent that the maximum secondary power occurs at ⅔ of the synchronous speed of the induction motor. The speed of the variable speed set is directly proportional to slip. The maximum current in the d-c loop occurs when the variable speed set is operating at minimum speed.

The synchronous generator that feeds power back into the supply system need only be large enough to handle the maximum secondary power, minus the losses in the motor generator sets.

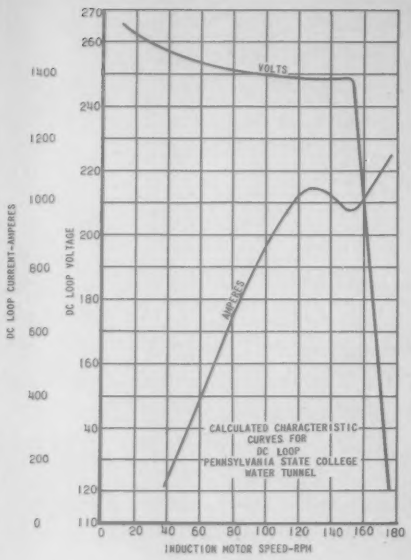
The best way to illustrate the operation of the drive is to describe the manner of connecting the system to the line. Refer to Figure 3 for the main interconnections of the machines.

The following auxiliary equipment is first put into operation:

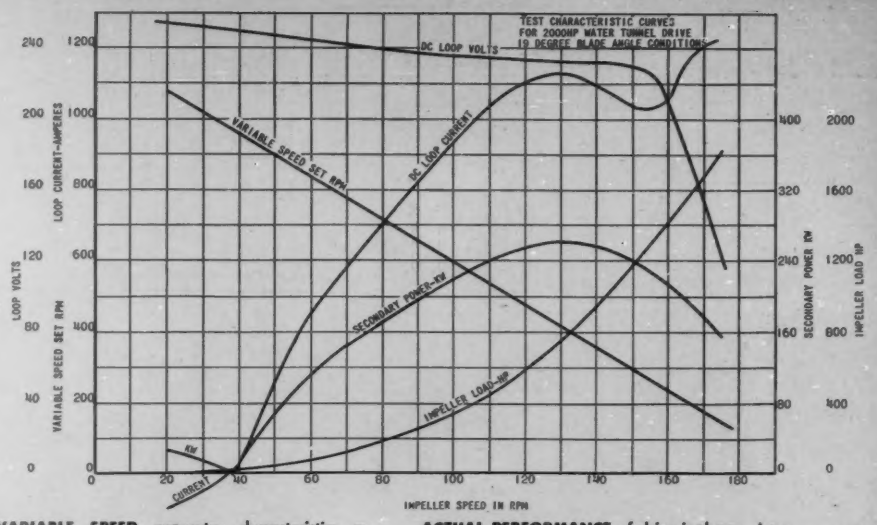
1. The lubricating pumps and ventilating fans.
2. The Regulex exciter set, which provides excitation for the d-c motor (machine D_2) of the constant speed set.
3. The exciter set (not shown), which provides excitation to the constant potential bus. The fields of the synchronous generator, machine S_2, and the d-c generator, machine D_1, are connected to this bus.

With all the auxiliaries running, the constant speed set is started by closing the breaker (device 152) which connects the synchronous generator, machine S_2, to the 2,300-volt bus. When the synchronous generator comes up to speed, the field is automatically applied, using standard field application control equipment sensitive to the induced frequency in the synchronous generator field.

After the field is energized, the d-c loop breaker (device 72) is closed automatically. The variable speed set now starts to accelerate under the control of the electronic speed regulator and the motor-operated rheostat, device RH-A. The rate of acceleration is determined by the speed of operation of the motor-operated rheostat, which starts moving from the posi-



VARIABLE SPEED generator characteristics as calculated are plotted at left. Flux values are in flux lines per square inch. **(FIGURE 5)**



ACTUAL PERFORMANCE of drive is shown. Loop current reverses at low speeds. Note how values check with calculated curves. **(FIGURE 6)**

tion calling for minimum speed of the variable speed set to the position calling for synchronous speed. During the period of acceleration, the field of the synchronous motor, machine S_1, is excited. The performance of this machine is the same as that of an alternator, with the impeller driving motor I (which is not revolving) acting as a transformer. A frequency is induced in the stator of the impeller motor which is brought to match that of the incoming supply line by changing the speed of the variable speed set.

The design of the units is such that the voltage induced in the stator of the induction motor is matched automatically to that of the supply line. However, the induced frequency must be matched manually by means of a synchroscope and a small tandem rheostat. One rheostat is connected in the electronic speed regulating circuit and the other is connected as a vernier in the field circuit of the d-c motor, D_2, of the constant speed set. When manual speed regulation is used, this field is excited from the constant potential bus rather than the Regulex exciter. Since the two rheostats are connected in tandem, the synchronizing operation is identical whether automatic speed regulation is used or not.

Starting causes minimum line disturbance

When synchronism is indicated, the operator closes breaker 252, which connects the impeller motor to the supply system. The impeller motor still remains stationary up to this time since there is no slip between the rotating fields of the rotor and stator of the impeller motor and consequently no torque is developed. A minimum of line disturbance, therefore, results in starting up the drive. This feature is advantageous since the water tunnel is located near the end of a rather long transmission line of limited capacity. After the impeller motor is connected to the line, the control is transferred to the remote control location, from which the tests in the water tunnel are conducted.

In order to start the impeller rotating, the speed of the variable speed set is gradually decreased by electronic control. The speed of the impeller motor is then proportional to the difference in frequency between the impeller motor rotor and the 60-cycle supply line. As the speed of the variable speed set decreases, the speed of the impeller motor increases. The design of the speed setting rheostat permits the speed of the drive to be changed in virtually stepless speed increments.

Water velocity can then be adjusted to any desired value from the remote test position. As soon as the desired velocity is obtained, the control takes over to maintain constant impeller speed, within ¼ of one percent, for the duration of the test.

To stop the drive, the impeller is brought down to zero speed. The circuit breakers for the impeller motor and the synchronous generator are opened and the motor generator sets allowed to coast to rest. The d-c loop breaker opens automatically when the synchronous generator breaker is opened.

During the starting period, the synchronous generator, S_2, acts as a motor and drives the constant speed set. The d-c machine, D_2, then supplies power through the d-c loop to the variable speed set. However, when the impeller is running, the power flow is reversed. The slip energy is returned to the line by means of the synchronous generator. Approximately 85 percent of the slip energy is returned to the supply line, over the four to one speed range.

When operating under manual control, the speed regulation of the drive is the combined inherent speed regulation of the various machines, which tests have shown to be 2.7 percent for a change of 40 percent of full load on the impeller. This speed regulation is excellent and is satisfactory for some tests that do not require precise control of the water velocity.

The type of drive used in the Garfield Thomas Water Tunnel is somewhat similar to those built for aeronautical research in wind tunnels. Much of the astounding progress of the aviation industry over the past two decades was made possible through research in modern wind tunnels, where speed, velocity and power measurements could be made to a high degree of accuracy. It is hoped that results of hydrodynamic research at the new Naval Ordnance Laboratory will contribute in a similar manner to the marine industry. Information obtained from the analysis and testing of this drive will be invaluable for the design of future large variable speed drives of all types.

BONNEVILLE'S 17,500/42,000-KVA SYNCHRONOUS CONDENSER is being loaded for shipment. The hydrogen-cooled, outdoor unit will be under Regulex control and will operate at hydrogen pressures up to 15 psi. Oval-shaped ports provide entry for inspection or removal of bearings. Exciter section can be sealed off during shutdown for inspection without loss of hydrogen from main compartment. *Allis-Chalmers Staff photo*

Coordinating CONTROLLER and BREAKER Ratings

Authors point up need for coordination between starter and breaker ratings — air contactor ratings extended.

by
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and
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Allis-Chalmers Mfg. Co.

CONTINUALLY INCREASING CAPACITIES of industrial electrical distribution systems have changed the requirements in the application of industrial control and switchgear. These increased electrical requirements may be due to plant growth, to modernization of manufacturing facilities or to production methods requiring additional electrical power. Such demands mean additional generators if power is generated or additional tie-lines with the power company if power is purchased. Larger substations, for more economical power distribution in parts of the plant located remotely from the power generation, may also be required. It often is necessary to replace 25,000-kva or 50,000-kva interrupting capacity feeder breakers with breakers with interrupting capacities of 100,000 kva or 150,000 kva. Under conditions like these, industrial starters that have been in service for years may no longer give adequate protection.

Table I lists the latest preferred ratings of indoor power circuit breakers, both oil type and oilless, with interrupting capacities of 150,000 kva or less, suitable for backup protection of industrial controllers.

All of the breakers in Table I have a nominal interrupting time of 8 cycles. Each breaker has three voltage ratings, the rated kv, the maximum design kv (maximum application voltage) and the minimum rated voltage for interrupting the rated kva of the breaker. Two current ratings are given for each breaker, one corresponding to the amperes at rated voltage, giving the rated kva interrupting capacity. The second or maximum ampere rating gives the amount of current in amperes that can be interrupted at the minimum rated voltage for rated interrupting ability. This maximum current must not be exceeded even though the breaker is applied on a lower voltage distribution system.

Figure 1 shows the line diagram of one industrial electrical distribution system which, like that of so many of today's plants, and like Topsy, "just grew" as the electrical requirements of the plant increased. The first generators installed had an output of 480 volts, three phase, 60 cycles. Later, as the

TABLE 1 — American Standard Schedules of Preferred Ratings of Power Circuit Breakers
(ASA C37.6, 1949)

	Voltage Ratings			Insulation Level		Continuous Rating Amperes			Interrupting Ratings			
				Withstand Test			Short Time					
	Rated KV	Max. Design KV	Min. Rated KV for Int. MVA	Low Freq. RMS KV	Impulse Test KV	Continuous 60 Cycles	Momentary	4 Second	3 Phase Rated MVA	Amperes at Rated Voltage	Max. Amperes	Time, Cycles
INDOOR OIL POWER CIRCUIT BREAKERS												
1	4.16	4.76	2.3	19	60	600	10,000	6,300	25	3,500	6,300	8
2	4.16	4.76	2.3	19	60	1200	20,000	12,500	50	7,000	12,500	8
3	7.2	8.25	2.3	26	75	600	20,000	12,500	50	4,000	12,500	8
4	7.2	8.25	2.3	26	75	600	40,000	25,000	100	8,000	25,000	8
5	7.2	8.25	2.3	26	75	1200	40,000	25,000	100	8,000	25,000	8
6	7.2	8.25	2.3	26	75	2000	40,000	25,000	100	8,000	25,000	8
7	13.8	15.0	4.0	36	95	600	35,000	22,000	150	6,300	22,000	8
8	13.8	15.0	4.0	36	95	1200	35,000	22,000	150	6,300	22,000	8
INDOOR OILLESS POWER CIRCUIT BREAKERS												
1	4.16	4.76	2.3	19	60	600	20,000	12,500	50	7,000	12,500	8
2	4.16	4.76	2.3	19	60	1200	20,000	12,500	50	7,000	12,500	8
3	4.16	4.76	3.5	19	60	600	40,000	25,000	150	21,000	25,000	8
4	4.16	4.76	3.5	19	60	1200	40,000	25,000	150	21,000	25,000	8
5	4.16	4.76	3.5	19	60	2000	40,000	25,000	150	21,000	25,000	8

plant size increased, it became uneconomical to distribute power at 480 volts, so three additional generators (8, 9 and 10) rated 2,400 volts were installed and the 2,400-volt distribution system was tied in with the 480-volt distribution system with transformers. The 2,400-volt system was segregated into three sections by means of 8,000-kva reactors designed to limit the maximum short circuit possible, permitting the use of 150,000-kva breakers. Finally, the 2,400-volt distribution system was outgrown and a 13.8-kv bus and 7,500-kw generator were added with provisions for an additional generator of equal capacity. The 13.8-kv bus was tied in with the 2,400-volt bus through two banks of 7,500-kva, 13.8/2.4-kv transformers. Air circuit breakers of 500,000-kva interrupting capacity are used on the 13.8-kv distribution system.

Suppose that a controller is to be selected for a motor located at point x in the system of Figure 1. The unit will be required to handle motor currents at the full load rating and specified overload ratings of the motor as well as currents up to the stalled rotor value, which may be four to seven times the rated full load value.

However, if a short circuit should occur in the motor windings or in the circuit on the load side of the controller, the controller must do one of two things:

(a) It must interrupt the short circuit and withstand the incident current mechanically and thermally while so doing, or

(b) It must withstand short circuit currents thermally and mechanically while a feeder circuit breaker clears the fault.

Starter ratings not coordinated with system

The system in Figure 1 is quite typical of the problem in many industrial plants and shows why contactors need to be coordinated with the distribution system. Unfortunately, contactors for use in industrial control starters also "just grew" without too much thought being given to coordination. Until very recently the standard high voltage device has been the oil contactor with an interrupting ability of ten times the motor full load current rating. This controller is designated a NEMA "Class A" controller. Where special industry requirements had to be met, as in the rubber industry, standard oil contactors were redesigned to withstand high through currents. The rating of these special controls was based on the maximum through current permitted by their design and established by test. Reactors were required, in many cases, in the circuit to keep the current within the contactor rating. These through current ratings have generally been based on a time of one second to allow clearing of the fault by distribution circuit breakers elsewhere in the system.

For larger motors in general, two types of controllers have been available. The engineer could choose either an oil contactor (or recently, an air contactor) with power fuses (Class E-2), or he could specify a controller using a circuit breaker[1] (Class E-1), in the 25,000-kva or 50,000-kva interrupting ratings. Both of these have had definite limitations.

The oil or air contactors were capable of handling motor currents up to stalled rotor values and were designed for repetitive starts and stops at short intervals. The power fuses were designed to clear short circuit currents. However, current limiting power fuses are not available for the largest size motors (as will be mentioned later) used in today's industrial plants. In addition the contactors were not fully proven for the through currents admitted on fault by the larger fuses. Such through currents approach values corresponding to the full interrupting capacities of modern distribution switchgear.

In Class E-1 controllers, the breakers while suitable for many applications, are not adapted to highly repetitive motor starting duty and are limited in interrupting ability.

Larger fuses slow to blow

Development of the high interrupting capacity current limiting fuse made it possible to use standard industrial contactors on distribution systems where the maximum short circuits did not exceed 150,000 kva on 2,500-volt systems or 250,000 kva on 5,000-volt systems. In application, these are selected to meet interrupting capacity requirements on the system at the point where they are connected, so that where several controllers are fed from one feeder breaker, a fault in one motor circuit does not shut down the remaining ones.

Fuses in the smaller ratings are very effective in limiting the peak amperes during fault interruption. With these fuses, peak

[1]The line of demarcation between control devices handling motor currents, and switchgear, has been found in practice and recognized in NEMA standards to be 50,000 kva and 5,000 volts. Thus, except where high voltage fuses are used to limit interrupting duty below these values, circuit breakers have been required for motor control.

TABLE 2 — Standard High Voltage Air Break Contactors for Heavy-Duty Motor Starting
200 Amp and 400 Amp — 5000 Volts — 25-60 Cycles

No. of Poles	Continuous Ampere Rating 8 Hr. Basis	KVA Interrupting Capacity at		Maximum Horse Power					
				2000-2500 Volts			4000-5000 Volts		
				Synchronous		Induction	Synchronous		Induction
		2500 V	5000 V	1.0 P.F.	.8 P.F.		1.0 P.F.	.8 P.F.	
3	200	25,000	25,000	900	700	700	1500	1250	1250
3	400	25,000	35,000	1750	1500	1500	3000	2500	2500
3	400*	50,000	50,000	1750	1500	1500	3000	2500	2500

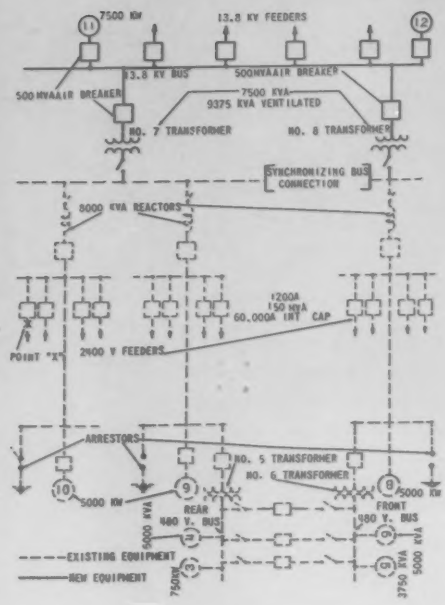
All ratings designed for following tests:

(a) 60 KV impulse

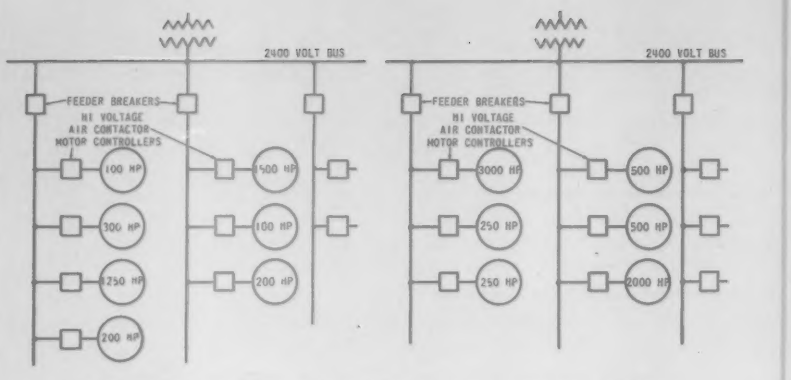
(b) 19 KV dielectric

(c) 35,000 RMS Amp momentary thru current with fuses

*50,000 KVA contactor has a thru current rating of 25,000 amperes for 30 cycles (0.5 seconds). For use on motor.



SYSTEM at left is that of one eastern manufacturing plant and illustrates need for breaker-controller coordination. **(FIGURE 1)**



HIGH through current rating of contactor eliminates power fuses. **(FIG. 2)**

amperes through the contactor during the interruption can be limited to 5,000 amperes on a system capable of producing 35,000 amperes (150,000 kva). However, fuses in the larger continuous ratings, being slower to clear, have very little current limiting ability and the contactor used with them must be able to withstand as much as 35,000 amperes through current, corresponding to nearly 150,000 kva at 2,500 volts or 250,000 kva at 5,000 volts, during the interval of the fault, until cleared by the fuse. Types of fuses that are not current limiting i.e., that do not blow or introduce resistance in the circuit within the first half-cycle, are also available. Because of high peak currents during fault interruption, the use of 50,000-kva contactors is frequently recommended where fuses are used with motors having starting currents of more than 400 amperes.

Circuit breakers required on large motors

Current limiting fuses may be used on motors where the initial starting current[2] does not exceed 1,300 amperes. This results in a maximum fused controller rating of 1,000 hp at 2,300 volts with correspondingly lower horsepower ratings at other power factors or different speeds in order to stay within the 1,300-ampere limit. When this rating has been exceeded, it has been necessary to resort to the switchgear class of equipment.

The circuit breaker as used in switchgear, is primarily designed for interrupting duty. Being a latched-in device, large forces are released on tripping in order to separate the contacts quickly. The mechanism is subject to considerable wear. Relatively large inertias are involved, both mechanical and electrical, with consequent long closing time (20 cycles is a typical figure, except where pneumatic operation is used). This delay is not too important in normal breaker applications, but in motor control involving forward and reverse, or forward, reverse, and dynamic braking, both the closing and opening time of the interruptor must be as short as possible.

[2]Initial starting current is considered as the RMS value of current drawn by the connected motor at standstill, and is determined by the synchronous impedance of the windings. The inrush current is the peak transient current, determined by the subtransient reactance of the motor, and is not normally a factor in selecting motor control as this transient disappears in a cycle or so. This is also the case if the short circuit is asymmetrical i.e. if it occurs at any other instant than that when the system voltage is at its peak.

New air contactor handles heavy fault currents

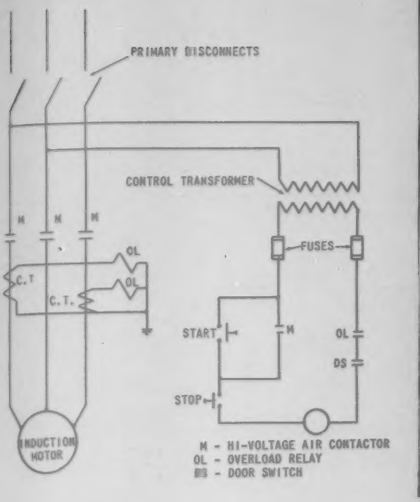
These limitations of both current limiting fuses and circuit breakers have resulted in disproportionately high initial and maintenance costs for control for motors above 1,000 hp, or 1,300 amperes initial starting current as outlined. A new design high voltage air contactor solves this economic discrepancy and opens up two new areas of contactor applications.

These new contactors, listed in Table II, can be used in the same manner as oil-immersed or air contactors with current limiting power fuses. Or, they may be used with power fuses that are not current limiting on systems where fault currents do not exceed 35,000 amperes (RMS). Unlike oil immersed units, the contact tips on these air contactors can open during the interrupting time of the fuse without appreciable damage to the contactor. And like other air contactors, they are particularly adapted to jogging or inching service, because the arc products, some of which are liberated at each interruption, pass off into the air.

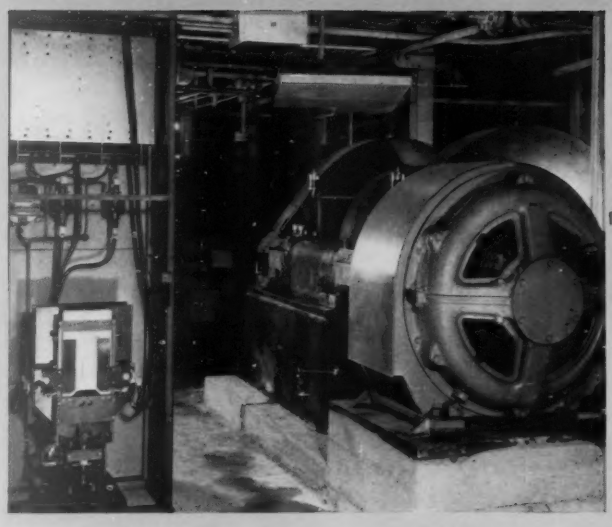
In addition, the new 400-ampere high capacity unit listed in Table II is specially designed to provide an interrupting capacity of 50,000 kva without fuses, and to withstand through current on faults of 25,000 amperes (RMS) for 30 cycles. This through current rating was selected to coordinate the design of this contactor with modern circuit breaker ratings as listed in Table I.

Circuit breakers provide safe backup protection

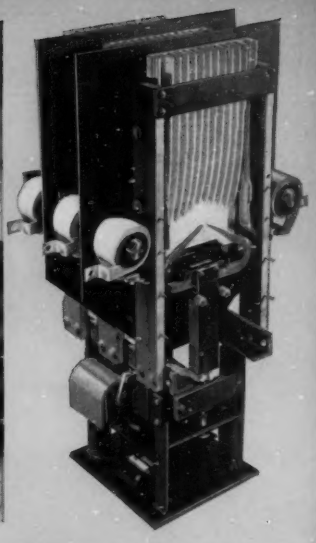
Figure 2 is a single line diagram of part of an industrial distribution system showing how the new high capacity contactors are used with circuit breakers to control five banks of large motors. Protection against overloading is provided by thermal relays in the control. These relays do not have sufficient time to trip on fault current, the circuit breakers tripping the fault current first. A diagram of an across-the-line starting controller utilizing the new air contactor is shown in Figure 3.



ACROSS-THE-LINE starter using high voltage air contactor in simplest form is shown. **(FIGURE 3)**



NEW AIR CONTACTOR in controller at left starts 300 hp motor once a minute 24 hours a day. **(FIG. 4)**



DEPARTURE from usual design makes high overload capacity possible. **(FIG. 5)**

The 50,000-kva contactor, for the first time, permits the application of a motor current handling device capable of repetitive, continuous operation to large motors, and, incorporating at the same time, adequate protection against damage to the controller from through currents for an appreciable time, if a short circuit up to 150,000 kva should occur. The half-second rating provides an ample margin of safety for use with circuit breakers with a nominal interrupting time of eight cycles.

These contactors have been given a 60-kv impulse test and a 19-kv, 60-cycle dielectric test. Unlike circuit breakers, they are not limited to 4,600-volt service, but may be applied on distribution systems or motors rated up to and including 5,000 volts, three phase. A 200-ampere, 5,000-volt contactor is shown in Figure 4. The floor space required has been held to the equivalent of that required by oil-immersed units so that they may be used as a replacement for devices having insufficient interrupting or through current-carrying ability. Pedestal type mounting permits easy mounting directly on the floor plates of the enclosure.

Figure 5 shows the new contactor with one-half of an arc chute removed to show design details. The double break contact principle was chosen because it eliminates flexible leads, decreasing maintenance appreciably. Two gaps in series initially cut the arc voltage in half, doubling the rate of dielectric recovery as compared to a single gap. Stationary contacts have integral arc runners and movable contacts have arc horns which will remove the arc from the contact area. Before rising into the arc chute, the two arcs leave the movable contactor arc horns and combine into one arc across the stationary contact arc runners.

The movable contact carrier was designed for slight movement both horizontally and vertically, rocking on the contact pressure spring. Equal pressure on both contact tips of each double break contact is thus assured. These contact springs also act as kick-off springs for fast contact separation when the magnet is de-energized. Adjusting the connector between the operating bar and the contact push-rod changes both the contact gap and pressure. Individual adjustment for each pole assures uniform values of contact gap and pressure for all three poles.

It was found advantageous to provide two blowout coils per phase, both located entirely out of the arc path. This dual blowout structure shortens interrupting time for all values of current within the rating of the contactor. The contactor operating mechanism has a straight line vertical motion, guided by hard non-magnetic pins that serve to reduce friction and maintain a uniform, balanced air gap throughout the life of the contactor.

Two- or three-unit combinations with mechanical and electrical interlocks are used for dynamic braking and reversing service and for reduced voltage starting. Figure 6 shows a three-unit structure for reversing dynamic braking controllers. Rollers provide for easy removal of the complete unit from its enclosure for periodic inspection.

CONTROLLER for rubber mill uses three contactors to provide reversing, dynamic braking for synchronous motor drive. Wheels on contactor assembly speed inspection. **(FIGURE 6)**

A NEW PRINCIPLE in Arc Interruption

by

A. E. HERMAN
Engineer, Control Section
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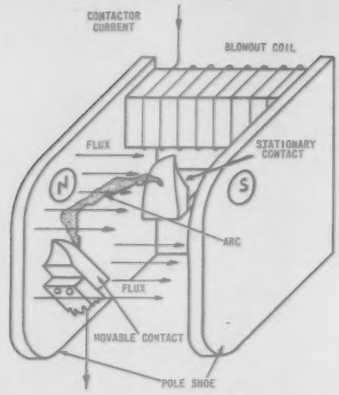
Simple new device incorporated in arc chute reduces arcing time in contactors.

TODAY'S CIRCUIT INTERRUPTORS have come a long way from the knife switches of years ago. Modern electrical machines allow current inrushes of several times normal rating during the starting interval while control circuits are such that, during plugging or dynamic braking duty, currents far above normal machine rating are allowed to develop. To safeguard today's machinery, contactors have had to keep pace with design practice and provide more reliable and positive circuit interruption.

In the field of low-voltage contactors (600 volts and less), a great many schemes have been developed through the years to improve circuit interruption by reducing the arcing time during the interval that the contacts begin to part and the moment of final arc extinction. The conventional method has been that of placing the arc in a strong magnetic field which is set up by the load current flowing through a blow-out coil. Figure 1 shows a simplified blow-out system illustrating how the magnetic field is set up transverse to the arc. Applying Fleming's Motor Rule, we find that, with the left forefinger pointing in direction of the flux, the middle finger in direction of the current or arc flow, the thumb indicates the upward



CONVENTIONAL BLOW-OUT COIL and magnetic structure is shown in this simplified contactor. Insides of pole shoes are normally insulated. Blow-out effect is independent of current direction. **(FIG. 1)**

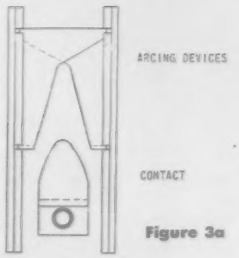


Figure 3a

FRONT VIEW OF ARC CHUTE

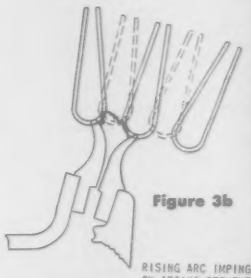


Figure 3b

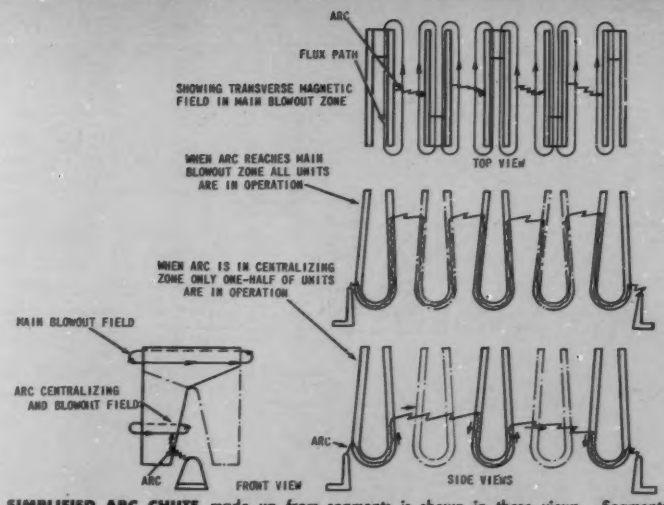
RISING ARC IMPINGES ON ARCING SEGMENTS

motion of the arc. This transverse magnetic field tends to lengthen the arc path to the point where it finally breaks and the arc is interrupted, and the surrounding air again becomes a dielectric. Numerous variations have been made around this basic principle. Various shaped plates or pins, both conductors and non-conductors, are used in these variations to break up and cool the arc path, thereby aiding in extinguishing the arc. Aided by such a magnetic field, modern circuit interruptors have been able to reduce arcing time to acceptable values.

In the course of a search for an improved contactor design a new type of arc chute has been developed which reduces the arcing time of a contactor. Through the resultant reduction

ARC INTERRUPTING TIME is cut drastically with new arc chute. At left, control engineers are examining segment from a dismantled 200-amp contactor. At right, the same contactor is shown under high current test on the test floor.

SEGMENTS MADE from electrically conductive metal act as individual blow-out coils in the arc path. **(FIGURE 2)**


ARC
FLUX PATH
SHOWING TRANSVERSE MAGNETIC FIELD IN MAIN BLOWOUT ZONE
TOP VIEW
WHEN ARC REACHES MAIN BLOWOUT ZONE ALL UNITS ARE IN OPERATION
WHEN ARC IS IN CENTRALIZING ZONE ONLY ONE-HALF OF UNITS ARE IN OPERATION
MAIN BLOWOUT FIELD
ARC CENTRALIZING AND BLOWOUT FIELD
ARC
FRONT VIEW
ARC
SIDE VIEWS

SIMPLIFIED ARC CHUTE made up from segments is shown in these views. Segments would normally be placed along the circumference of movable contact path of travel. Higher voltage contactors require more segments in series in the arc path. **(FIGURE 4)**

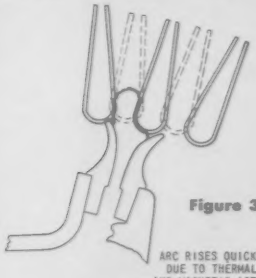


Figure 3c

ARC RISES QUICKLY DUE TO THERMAL AND MAGNETIC ACTION

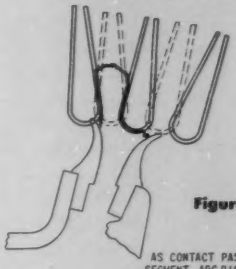


Figure 3d

AS CONTACT PASSES THIRD SEGMENT, ARC RISES BETWEEN FIRST AND THIRD UNITS

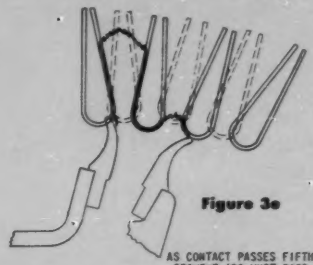


Figure 3e

AS CONTACT PASSES FIFTH SEGMENT ARC MUST PASS ACROSS NEW GAP

in peak arc current, vaporization of contact surface material is lessened considerably and contact operating life is expected to be much greater.

The construction of the new interrupting chute is shown in Figure 2 and Figure 3. The individual devices shown in Figure 2 each consist of a metal plate formed into a somewhat "U"-shaped cross section, the "U" being widest at the bend and tapering inwards towards the ends. Viewed from the front, the stamping resembles a right angle triangle with the vertex pointed down into the plates adjacent to the bend. The individual devices, insulated from each other, are made of electrical conductive material, and are placed at right angles to the circumference of contact travel.

Thermal effect deionizes arc path

The device begins to take effect only after the arc is drawn between the contacts, and its operation is not related in any way with the method of securing the tripping impulse on the contactor. Blow-out action starts to take place after the arc between the interrupting contacts impinges upon the device, and is a result of a combination of thermal convection and magnetic action. Figures 3a to 3e show how a group of the devices assembled into an arc chute interrupt the arc.

(a) The impinging arc strikes the devices. As it does, the current passes along the surfaces and through the elements as shown in Figure 3b.

HIGH SPEED MOTION PICTURES taken at 3600 frames per second show how devices blow arc upward. Tests were made at 324 amperes, 440 volts a-c on a 150 ampere contactor. **(FIGURE 5)**

(b) The movable contact continues to move to the right, "pulling" the arc around the loop of the device. This pulling through of the arc is continued from one element to the next, with the resistance of the arc path increasing as the number of gaps between elements increases, while the metal elements help to cool the arc path.

Magnetic blow-out does most of job

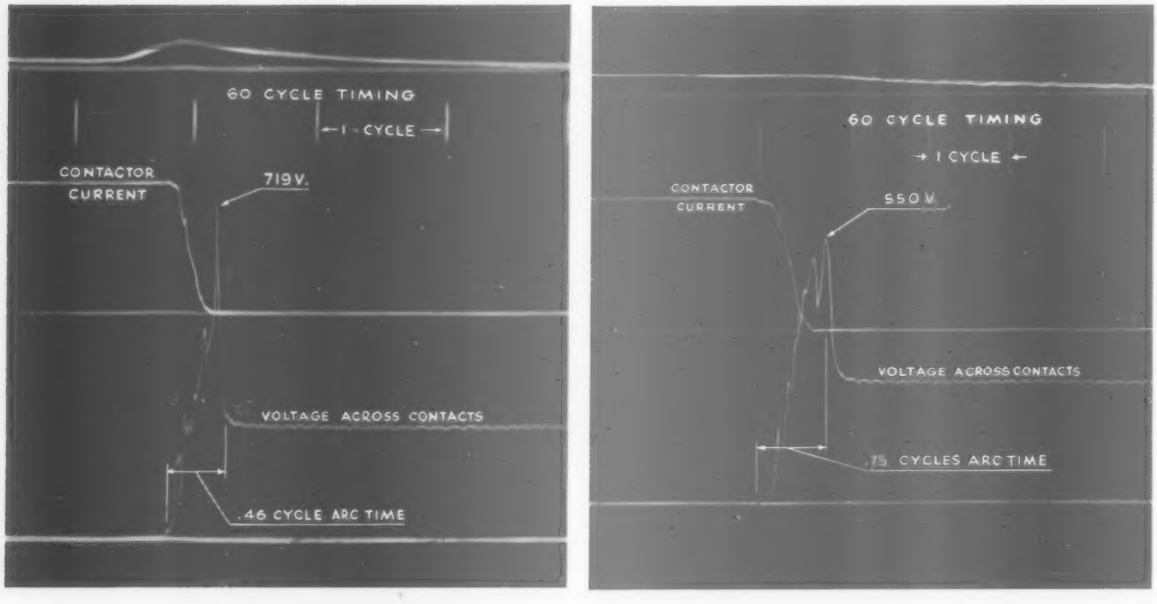
While the action just described is under way, a magnetic effect is taking place which plays the major part in extinguishing the arc. Figure 4 shows this magnetic effect. Assume that the arc has been pulled through until the arc current path is that shown in the lower figure. Here the arc current which impinges on the extremities of the elements sets up a magnetic field which forces the arc to move toward the arc centering zone. Since this magnetic field is transverse to the arc current it also functions as a blow-out zone.

The centralized arc, if not extinguished by the centralizing magnetic field, will continue to rise due to the magnetic action, entering the main blow-out zone. Here the current in the elements sets up a very strong transverse magnetic field similar to that of the conventional field of a blow-out coil. Also located in this main blow-out zone is the main blow-out zone of the heretofore inactive elements which are located on the opposite side of the arc chute. The rising arc now impinges on these inactive elements which suddenly doubles the blow-out ampere turns and thereby increases the strength of the transverse magnetic field. Each of the interrupting elements thus acts as an individual blow-out coil, extinguishing the arc so quickly that contact erosion is a very minimum. During the interval that the arc is passing through the blow-out segments, the air gap between contacts is cooling and re-establishing dielectric properties, greatly reducing the possibility of the arc to re-establish itself. Figure 5 is a series of three high speed motion pictures showing how the arc is dispersed through the arc chute.

The advantages of the new arc chute are readily apparent in the test results and oscillograms taken during the development of both a-c and d-c interruptors. A great many such tests have been made and, as the device is adapted to the full range of contactor ratings, many more will continue to be required to investigate all the factors in element shape and contour, spacing and position, as well as adapting the entire assembly, contacts, mechanism and trip coil to the higher interrupting speeds and overload capabilities possible with the new design.

Tests of d-c mill type contactor

A series of tests were made on 600-ampere steel mill type contactors over a wide current and voltage range, using the conventional as well as the new arc centering segments in conjunction with a blow-out coil. To obtain comparable data, identical tests were conducted on several standard makes of 600-ampere mill-type contactors.



OSCILLOGRAMS made during interrupting tests at 650 amps, 250 volts on 600-volt, d-c, mill-type contactors are shown. Figure 6a (left) shows higher interrupting speed of contactor equipped with arc-centering chute compared to standard contactor in Figure 6b (right). **(FIGS. 6a and 6b)**

Interruption at 650 amperes, 250 volts were typical of the performance during most of the tests and are tabulated in Table A. Figures 6a and 6b show typical oscillograms taken during the tests in Table A.

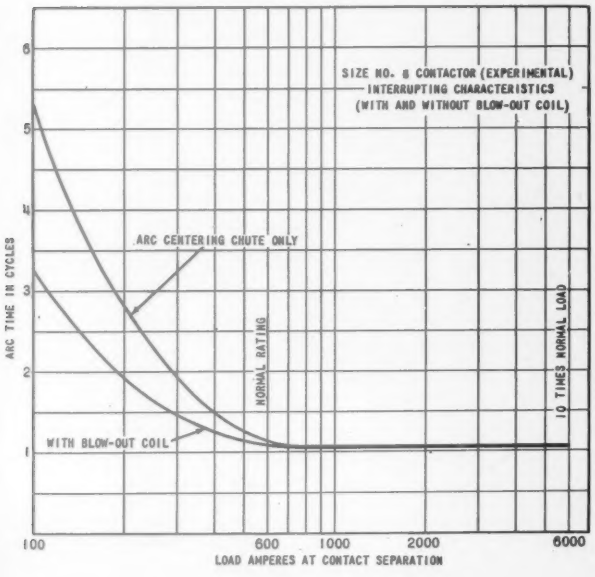
TABLE A

Type of Contactor	Interrupting Time in Cycles
Arc Centering Chute Design	0.46
Conventional Chute	1.49
C	0.91
D	1.30
E	0.75
F	1.72
G	1.1

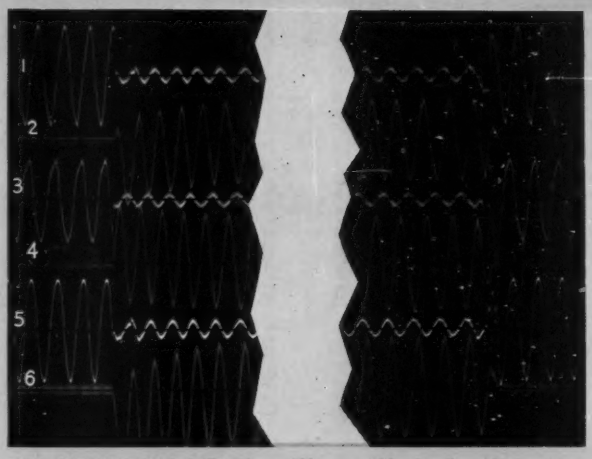
Following these tests, load current was increased for the contactor with arc-centering chute design. At 10,100 amperes arcing time was 0.98 cycles for the arc-centering equipped chute. This was 16.9 times normal rating and 69% greater overload than that required of any starter according to NEMA Standards. A great number of tests were made without damage to the contacts in spite of repeated surges. It was observed that with the new blow-out device a very minimum of arc gases were produced, indicating interruption in air rather than in a metallic vapor cloud. The oscillograms show a practically straight line relationship of arc voltage and time, indicating the rapid rise of arc resistance and dielectric recovery properties.

AC interruption tests on starters

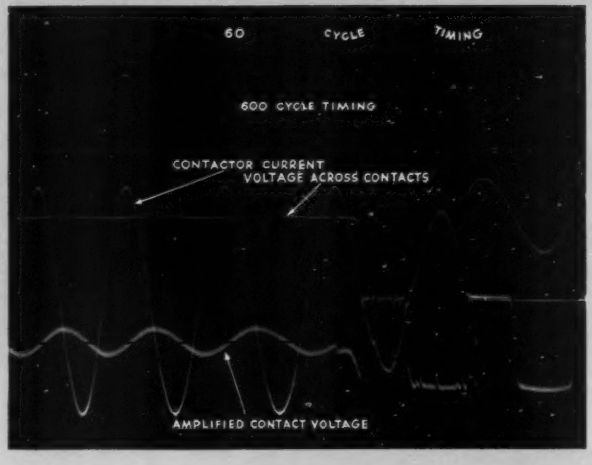
Tests have been made over a wide range of contactor sizes, showing marked improvement in all ratings when a properly



TESTS based on conventional contactors show blow-out coils to be advantage only at low current values. Later tests on special arc-centering equipped contactors have eliminated this low current differential. **(FIGURE 9)**



OCO INTERRUPTING TEST of a 900-amp, 600-volt, three-phase, a-c starter is shown in the oscillogram. Elements 1 and 2 show phase A (420 volts, 9,400 amps); elements 3 and 4 show phase B (330 volts, 8,800 volts); elements 5 and 6 show phase C (390 volts, 9,500 amps). Arc time for all phases was 1½ cycles in spite of very low power factor. **(FIGURE 7)**



EXTREME OVERLOAD TESTS at 13,470 amps, 500 volts were conducted on one-phase of a 600-volt, 900-amp (NEMA size 7), a-c starter. Elements and their connections are as follows: 1 — 60-cycle timing; 2 — 600-cycle timing; 3 — blank; 4 — voltage across contacts; 5 — contact current; 6 — voltage across contacts, amplified (with peak voltage cut-off). **(FIGURE 8)**

NEW ARC CHUTE greatly extends contact life in spite of repeated overloads. Without chute, copper would erode beyond repair. **(FIGURE 10)**

designed arc centering chute is applied. Figure 7 shows an oscillogram made during the test of a 900-ampere (Size No. 7) contactor. Current values are given. At this load (approximately 10 times normal) no molten metal was thrown out from the contacts and the interruption was accompanied by a white flash and a rather loud report. This contrasts with the more muffled report and orange arc glow of standard interruptors of this rating at high overloads. Because the arc is interrupted so rapidly in the new arc chute, vaporization of the contacts provides no metallic vapor cloud with its characteristic color. The louder report is a natural result of the more rapid extinction of the arc. Figure 8 shows a later test on one phase of the same contactor at 13,470 amperes. Note that interruption began at the most difficult part of the current cycle.

Another series of tests was performed on a number of experimental 3-phase 440-volt 600-ampere contactors (Size No. 6). Provision was made to shunt out the one-turn blow-out coil during part of this test. Figure 9 shows comparative arcing times with and without the customary magnetic blow-out coil. It is interesting to note that at normal loads and above, interrupting time is practically the same whether or not the blow-out coil is used. At low current values, the blow-out and arc centering action is not quite as rapid, but the extra one or two cycle arc time is of relatively little importance because of the small current involved. The difference is a result of the added time needed for the smaller arc to rise into the arc chute. It is quite possible that further changes in experimental chute designs may cut arcing time still further at low current values.

Contact erosion greatly reduced

There are two locations in an interrupting device where trouble is most likely to develop when the unit is subjected to repeated overloads, the contact, and the arc chute. The arc centering function of the elements means much less carbonization on the chute walls, over previous designs.

Erosion caused by the arc can very quickly ruin a set of contacts if the interrupting time under overload is not kept extremely short. An idea of the improvement in erosion loss on 600-ampere contacts is shown in Figure 8. The contacts are shown as they looked after removal from a 600-ampere experimental starter. All testing had been done on this same set of contacts. In addition to a great many tests at rated current and below were included 70 interruptions spread between 700 and 11,000 amperes, and two interruptions above 13,000 amperes.

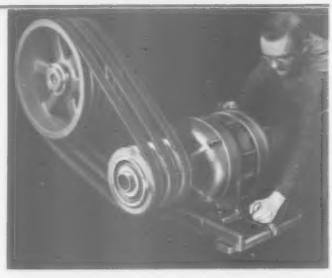
Chute opens new possibilities

Most of the tests up to this point have been conducted using adaptations of modern contactors. The simplification or elimination of the magnetic blow-out coil may provide reduced overall contactor size. Replacement of contacts on heavy mill contactors subject to extreme surges is expected to be sharply reduced as the burning away of the arcing tips is curtailed.

Additional tests and development of complete new designs built around the new arc centering chute points the way to contactors reduced in both size and weight, yet providing quicker interrupting time and greater overload capacity over long periods of time without maintenance.

New Products

Automatic Sheave Provides 'Twist of the Wrist' Speed Control of Running Drives

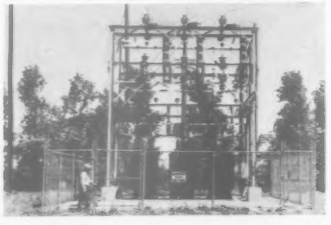


A recently developed speed control makes possible frequent speed changes and other adjustments while the drive is operating. Speed adjustment with the new unit has been reduced to a matter of seconds compared to the 10 to 15 minutes required to change speed on a stationary control sheave.

Consisting of a new Vari-Pitch automatic sheave, companion sheave, wide-range Texrope belts, and Texslide motor base, unit assures easier and smoother starting. It is being used for motion control speed change ratios up to 2 to 1. A simple turn of the adjusting screw on the Texslide motor base with any commercial wrench changes speed without delay or wasted effort.

Drive is especially suitable for high starting torque applications since it permits belts to ride at smaller pitch diameters during acceleration. It can be mounted at almost any angle while the motor base remains in horizontal position. Movement of angular faced discs towards or away from each other changes the diameter of the sheave as desired. An automatic belt tension stabilizer provides the proper sidewall pressure and belt tension regardless of the position of the belt in the groove. New sheave is standardized to accommodate standard motors from 1½ to 40 horsepower with motor speeds from 900 to 1,800 rpm.

Standardized Rural Substations Simplify Purchasing and Installation



Two types of standardized rural substations designed to meet nearly all power distribution requirements are now available for REA cooperatives and many utility applications. Basic designs have been established for incoming line voltages of 23, 34.5, 46, and 69 kv for high voltages and up to and including 14.4/24.9 kv wye for the low voltages, and in ratings from 300 up to 3,000 kva.

The type RSS substation for use where three or more three-phase feeders are required consists of a high voltage structure, and a low voltage distribution structure with a suspended bus between them, connected to the transformers. The basic low voltage structure consists of two bays with a low voltage bus. This structure can be made to serve more than four feeder circuits by the addition of more bays. Adequate space is provided on the low voltage structure to mount regulator bypassing equipment, metering transformers, hook-operated fuse disconnects, oil circuit reclosures, and line type lightning arresters for the feeder circuits. Structure may also be modified to accommodate the use of oil circuit breakers on the feeder circuits.

The type RIS substation consists of a single structure and is suitable for one or two three-phase feeder application. It is more compact than the larger capacity unit, with transformers placed inside the structure. If required, regulating equipment is installed beside transformers.

Lightning arresters are used on incoming high voltage lines of both types and are normally supplied for the feeder circuits. Although gang-operated air-break switches and fuse disconnects with power fuses are usually adequate, power oil circuit breakers can be used with either type of substation. Designed for three or four single-phase transformers, all designs are readily adaptable for a three-phase transformer. Normally supplied three-phase regulator can be replaced with three single-phase regulators.

Loading Evaluation of TRANSFORMERS

by

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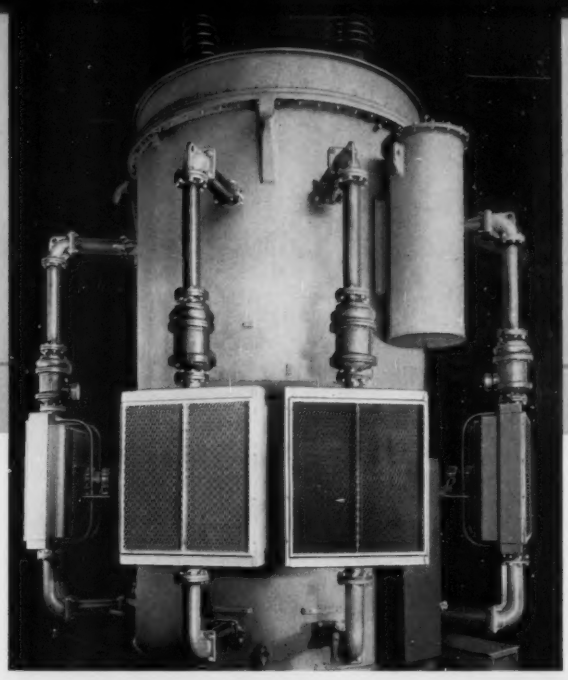
Engineer
Transformer Section
Allis-Chalmers Mfg. Co.

Author outlines some little understood principles in transformer cooling and its relation to application economics.



FORCED-OIL COOLING with oil-to-air heat exchangers (Class FOA) greatly increases transformer rating, uses little space. **(FIGURE 1)**

THE TENDENCY TODAY for transformers as well as for so many other types of equipment is standardization. If a purchaser buys a "standard" unit, it may be in stock, or is, at least, already designed and developed, and ready to be put into shop production when the order is received. This means some saving in cost and probably a shorter shipping date, besides giving greater flexibility to a system through interchangeability of apparatus. Losses, ratio of copper to core loss, and impedance of transformers are well standardized for such designs. Temperature limits at rated full load are set by ASA Standards at 55 degrees C for average copper rise, and 65 degrees C for maximum hot spot rise.

Large power transformers, however, are usually custom built to suit special requirements, although this may mean an increase in cost and in losses due to the special arrangements and features specified by the user. He may want a transformer as near "standard" as possible. On the other hand, he may have a system where the load factor is low, but occasional overloads are high. Or his loading condition may be temporary and the future use of the transformer uncertain. The user may also have an urgent need for the equipment, but only a limited amount of money available in his budget and he feels compelled to buy something for which the first cost is less, although the operating costs will be more and, in the long run, the total cost will actually be higher.

Fortunately, for a given transformer installation with a given kva output rating, the designing engineer is not necessarily limited to a certain definite size of core and coils, with definite characteristics and total losses at full load, thus requiring a definite amount of cooling by one means or another. It should be understood that there is a considerable measure of flexibility in the design of working parts of a power transformer.

The low cost, low efficiency class of transformers includes the forced-air and forced-oil cooled units. The more the cooling is forced to obtain a certain rated kva, the higher are the losses at that kva, and the lower the efficiency. In other words, they become low efficiency transformers.

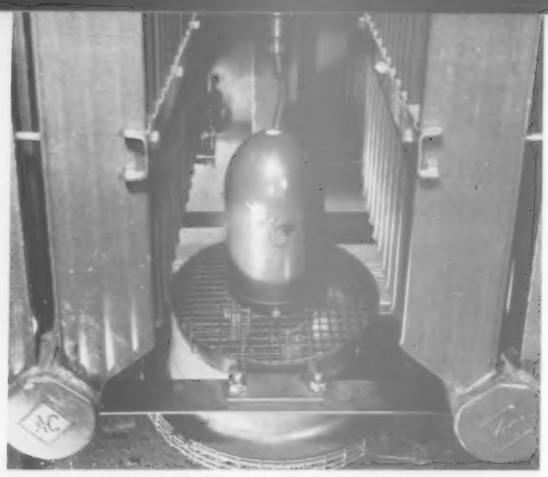
Rating increase with forced-cooling not fixed

The amount, or percentage, that the rating of a transformer with normal, natural cooling can be increased by forced cooling, with a consequently lowered efficiency at that forced cooling rating, is not a definite figure, except as fixed by more or less standardized practice. Originally, 15 to 25 years ago, self-cooled/forced-air-cooled transformers were sold with a forced-cooled rating of 150 percent of the self-cooled rating. Later, the majority were built with 133⅓ percent forced-air rating, with subsequent additions of a line of 125 percent ratings and 166⅔ percent ratings, respectively. Presently, the last three rating methods are common, since the standards do not specify actual values.

The only requirement by the American Standards Association is that the average copper rise does not exceed 55 degrees C and the maximum hot spot rise is not over 65 degrees C. It is perhaps just as simple and just as good engineering to rate up to any other figure between these values, or perhaps even higher, using any kind of cooling that is economical and that meets the user's requirement. It does not matter whether cooling is provided by conventional fans, by special high capacity or high velocity fans, or by circulating the oil with pumps and cooling it by oil-to-air or oil-to-water heat exchangers. All of these forced-cooled ratings are good for continuous operation under those conditions, if the units are built to stay within the winding temperatures specified by ASA. Figures 1, 2 and 3 show some of the different means used for obtaining these forced-cooled ratings.

Therefore, as far as engineering is concerned, the user is able to specify a transformer design tailored to meet his requirements, perhaps with the core and coils cut down and therefore worked harder to reduce the initial cost, and the amount of cooling increased to take care of the extra losses.

In the long run, the total cost of the transformer is the



FORCED-AIR cooling (Class OA/FA) is simple method of raising transformer rating. **(FIGURE 3)**

FORCED-OIL cooling with oil-to-water heat exchangers (Class FOW) raises this transformer rating to 1667 kva. **(FIGURE 2)**

original cost plus the upkeep and operating costs. The original cost of the transformer is determined by the amount of material and labor put into the transformer, while the operating costs and upkeep are determined by the cost of the energy which must be spent to make up the losses when the transformer is in operation, and the maintenance of the cooling equipment used. For a given load, these losses are not all proportional to the amount of material in the transformer, as was the first cost, but may vary inversely with the material used. Therefore, in general, the smaller the transformer the less the first cost, but the greater the losses, or upkeep, and vice versa. The user can figure this total cost for himself since he knows the conditions on his system.

Consider transformer made up of two basic parts

For the design engineer, a transformer must be considered as consisting of two parts: first, the active material, that is, the core and coils which do the work required and, in so doing, produce losses; second, the cooling equipment which dissipates the heat produced by those losses and holds the temperature of the transformer down to the standards established for such apparatus. The original cost is determined by the sum of two items, one of which recedes as the other rises. There also is a point where the sum of the two is a minimum.

Furthermore, there are two kinds of active material within the core and coils. These are the iron laminations of the core and the turns of copper conductor wound about the core. Since the flux density within the iron is a fairly fixed value, an increase in the number of turns of conductor permits a reduction of the cross section of the core, and vice versa. Therefore, for a given kva load, the ratio of copper loss to core loss can be varied by varying the turns of copper and the cross-section

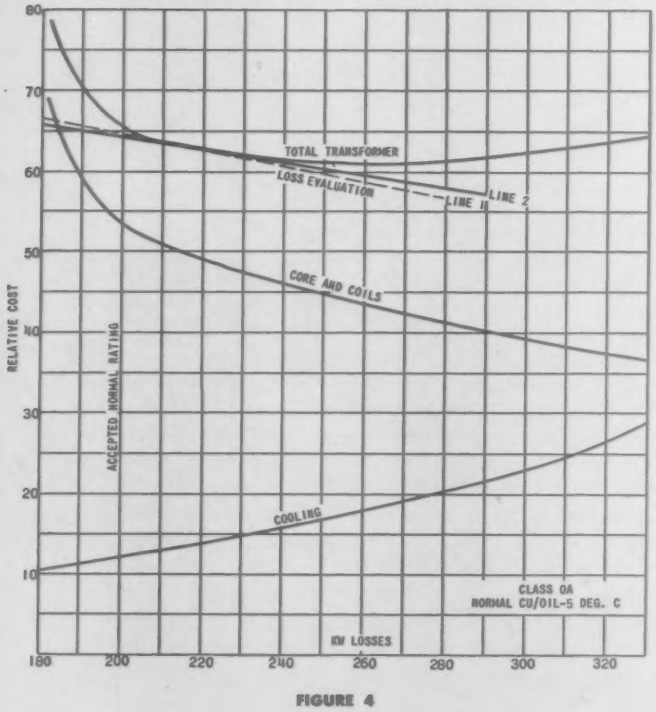


FIGURE 4

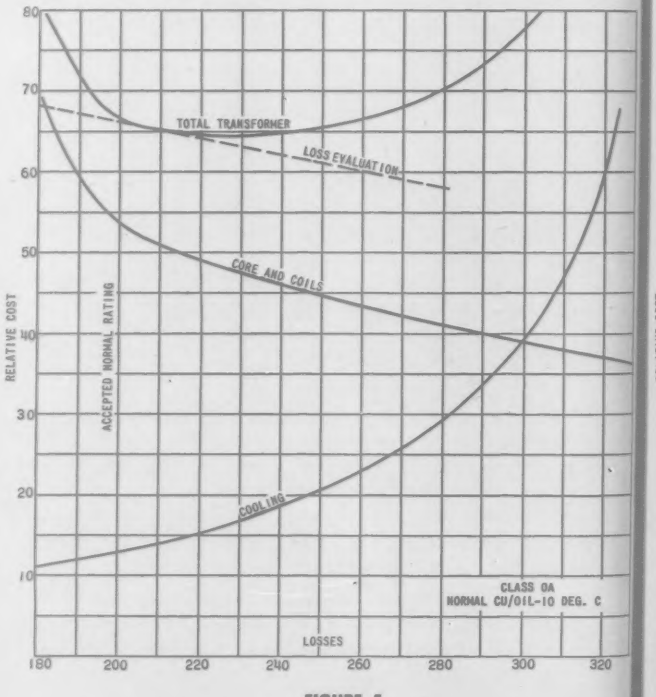


FIGURE 5

of iron used. It should be noted that losses can be stated in terms of product of copper and core losses at rated full load. If this product is held constant for a given rating, the maximum efficiency is also held constant but occurs at different loads for different full load ratios of copper loss to core loss.

Over a certain range this "loss ratio" can be varied without much change in original cost, though it may mean considerable change in cost of operation to the operator, depending upon how near his loading is to full load. It may also mean considerable change in impedance at rated kva. Also, for a given core and coil assembly, the kva load can be varied widely, with the core loss remaining constant, while the copper loss varies as the square of the kva load. In this case, the impedance varies directly as the kva load carried.

Total cost determined by sum of two parts

The next consideration is "For a given kva load, what will be the total 'first cost' of the transformer for different sizes of core and coil assemblies when operated at normal load, at overload, or at less than normal load, to carry the given kva?" This question applies to all transformers whether with natural air cooling (class OA), with forced-air cooling (class OA/FA), with water cooling (class OW), or with forced-oil cooling (class FOA or class FOW).

To answer this, it is first necessary to divide the cost of a transformer into that of the core and coils and that of the cooling equipment. Included with the core and coils are the tank, oil and bushings. These are independent of the cooling, except that for the water-cooled (class OW) transformers there may be a small increase in the size of the tank if there are internal cooling coils. This has but little effect on the cost of the unit.

The division into cost of core and coils and that of the cooling is done by the designer by first figuring the total kilowatts loss at full load for the transformer rating. For both self-cooled and water-cooled units these will be the same and the cost of cooling can be figured for each by using the proper value for cost per kw of loss for each type. The core and coils will be the same for both types of cooling and, therefore, costs will be the same for both. For forced cooling of various types the division, of course, will be different. The core and coils being overloaded will be smaller and the losses larger to an extent depending upon the amount of overloading. The cost per kw of the cooling will also be different, depending upon the type of cooling used.

For a self-cooled (class OA) transformer, curves showing such a division are given in Figure 4. These curves are based on a fixed output of 40,000 kva being obtained from core-and-coils units of different normal ratings, which result in total losses at the given kva output as shown by the abscissae. A constant impedance value at the given load is assumed and the ratio of losses at the equivalent "normal" kva is varied to suit the ratio required.

The curve showing the cost of cooling equipment is not, as might be expected, a straight line with the cost varying directly with the total losses. If the oil temperature remained the same this would be true, but the greater the load on a given size core and coils the greater the temperature gradient between copper and oil temperatures. Consequently, the oil rise must be reduced to maintain the same copper rise above ambient. Thus the amount of cooling equipment increases faster than the number of kilowatts to be dissipated, resulting in a cooling cost curve which curves upward at an ever increasing rate. This curve added to the core-and-coils cost curve gives the total original transformer cost, as shown by the third curve.

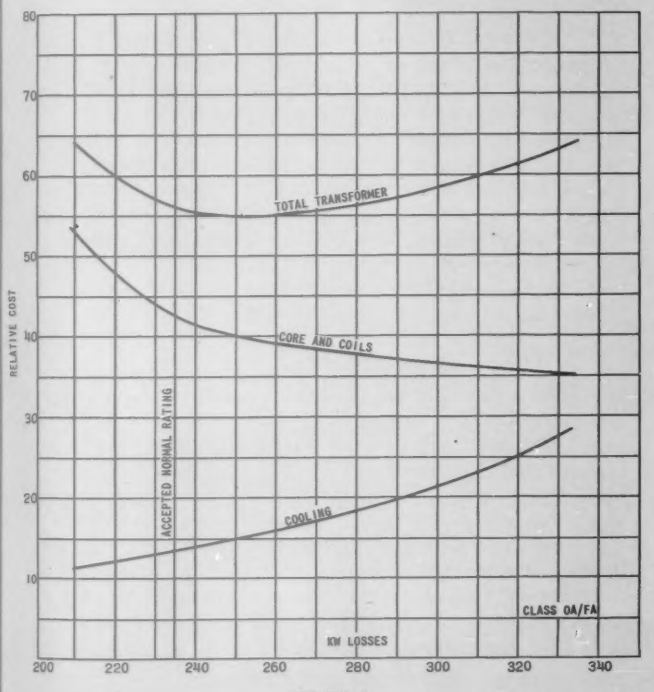


FIGURE 6

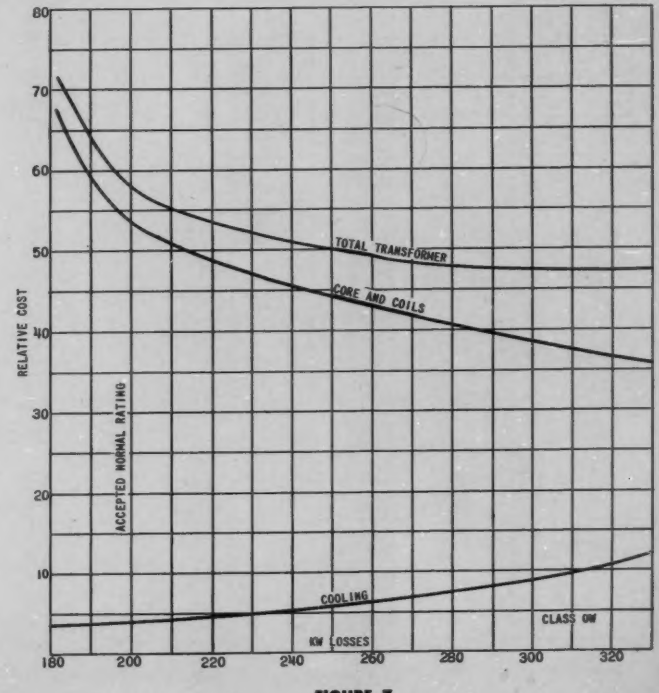


FIGURE 7

It should be noted that the slope of the cooling cost curve and, therefore, the total cost curve, will depend very decidedly upon the gradient between copper and oil at normal load, and upon the rate of temperature change with variation in losses. In the curves of Figure 4, a gradient of five degrees C at normal load between average copper and top oil, with temperatures varying as the 0.8 power of the losses, has been used. In Figure 5, curves have been drawn with an assumed 10 degree C gradient, but with other conditions remaining the same.

For both Figure 4 and Figure 5, the core and coils having a normal basic kva equal to the required kva output, that is, a core and coils operated at a load equal to its normal rated self-cooled capacity, have a total loss of approximately 200 kw. However, the minimum original cost is that of a core and coils having a total loss at the required load of approximately 265 kw for Figure 4, or 230 kw for Figure 5.

Tangent shows minimum cost

For the user who evaluates losses, the minimum cost point is somewhat different. If, for example, he figures $100 per kw for total losses at full load, a line drawn tangent to the total cost curve and sloping at 100 units per kw or 10,000 per 100 kw contacts the total cost curve at his minimum cost point. Such a line (loss evaluation line 1) is tangent at approximately 215 kw for Figure 4, or 210 for Figure 5. That these would be the points for least total cost can be shown as follows:

If the losses did not cost anything, the total cost to the user would be that shown by the curve, and a straight edge laid horizontally across the figure would be tangent to the curve at the lowest point, which would be the minimum cost. But if losses were valued at $100 per kw, moving to the left by one kw would reduce the total cost by $100, which could be shown either by lowering the curve or raising the reference axis. As we move further to the left a point is reached when the cost curve rises at the same slope, i.e., as the losses decrease $100, the cost curve increases $100. Here the straight edge, at the same slope as the reference axis is tangent to the cost curve and this point represents the lowest total cost with losses figured at the given value. A further move to the left would bring an increase in transformer cost of more than $100 for each kw saved and so would increase the total cost.

It should be noted that as we move to the left the size of the core (and, therefore, the core loss) increases, while the copper loss decreases more than the total loss indicates. Therefore, if the core loss were evaluated at a figure higher than copper loss, as is often done, the total loss evaluation decreases at a slower rate and the slope of the reference axis would be less, with the point of tangency moved slightly to the right. However, the shift is not enough to change the location of the point of minimum total cost by a great amount, probably 10 kw at the most. For example, in Figure 4 the loss evaluation line 2 shows the slope of the reference axis for an evaluation of $300 per kw for core loss and $100 per kw for copper loss.

Curves similar to those in Figures 4 and 5 can be drawn for other classes of cooling. Figure 6 is drawn for self-cooled/forced-air-cooled (class OA/FA) transformers; Figure 7 for water-cooled (class OW); Figure 8 for forced-oil-cooled (class FOA) transformers, all rated for a 40,000-kva output. Some details differ, but in general the principle is the same as for the self-cooled (class OA) transformer.

Discussion outlines wide choice of combinations

In all these curves the minimum original cost falls at a point to the right of that for the usual design of transformer having a normal kva equal to the kva of the load to be carried. In other words, standard designs have somewhat more material and, therefore, somewhat lower loss than units which could theoretically be built cheapest. This is a result of the traditional effort to build (or purchase) more efficient transformers in spite of the higher first cost.

Discussion of these various factors is not intended to indicate that it is practical for transformer manufacturers to design and build any and all of the possible ratings that might be obtained by special forced cooling combined with special ratio of losses and special reactance. Such a multiplicity of designs would, of course, mean that the manufacturer would very seldom, or never, be quoting on a duplicate of a transformer built previously. There are many disadvantages to such a condition, although it is not much different from that which now exists in the field of large transformers, due to the many types of cooling and the different efficiencies available.

It is intended, however, to show that there is a great deal of variation possible in the design and application of a transformer for a particular installation. The system engineer has the choice of any combination within the extremes of the liberal amount of material (and low losses) and the smaller core and coils with materials worked harder (therefore, with higher losses) and an increase in the amount of cooling provided. The total cost to the user consists of the sum of the cost of the core and coils and the cooling required plus the cost of the power required for taking care of the forced cooling and the maintenance and supervision of that cooling. For each installation this requires careful weighing of the different cost items to obtain the best value for the system under consideration.

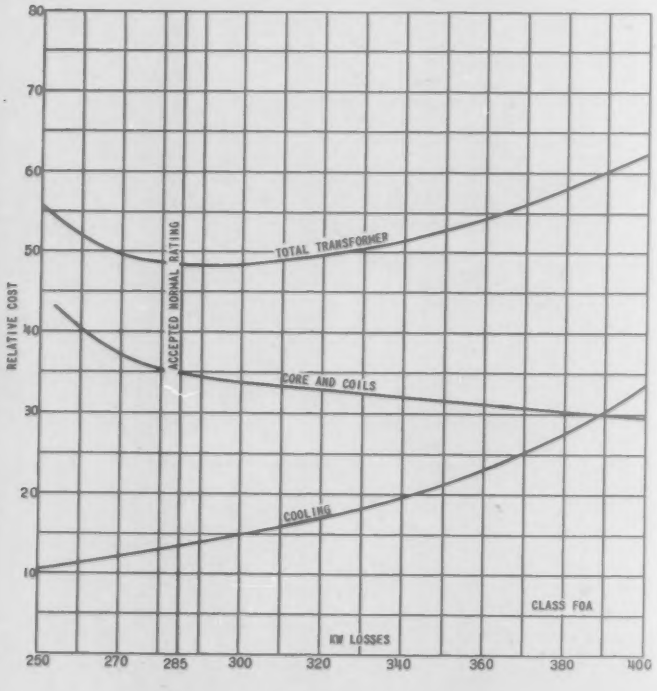
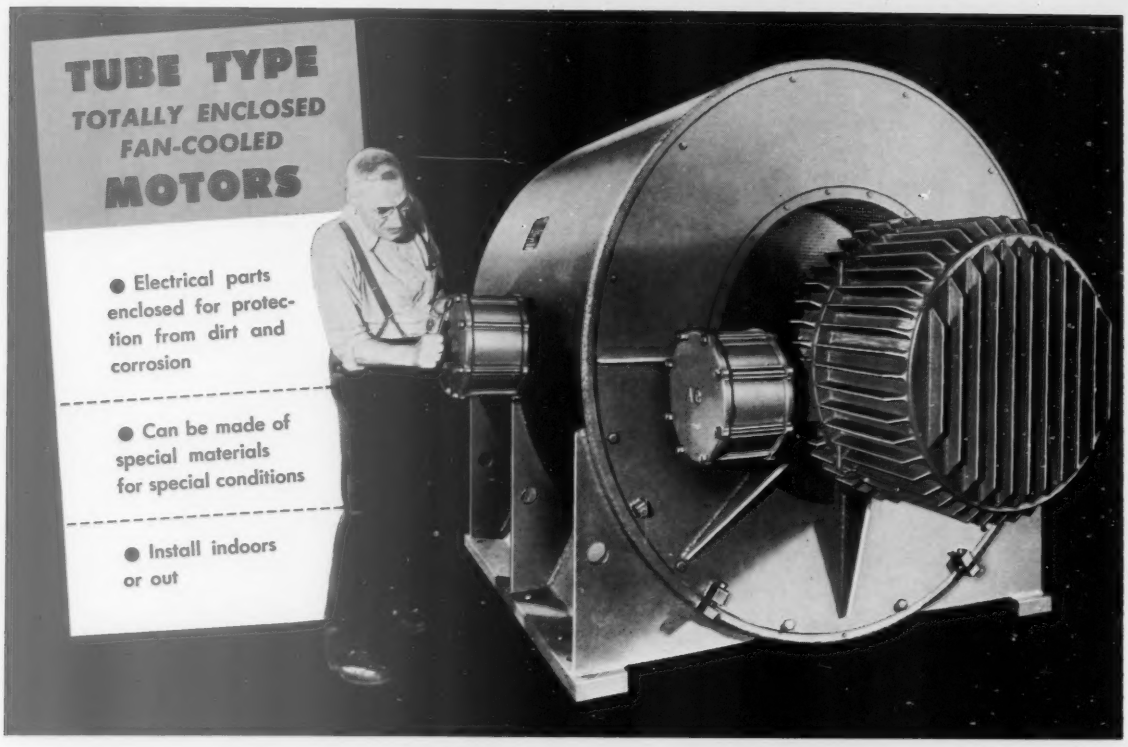


FIGURE 8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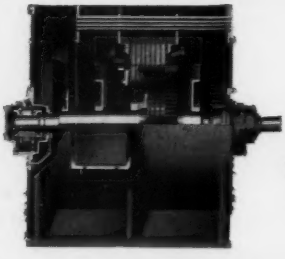

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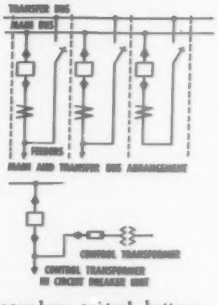
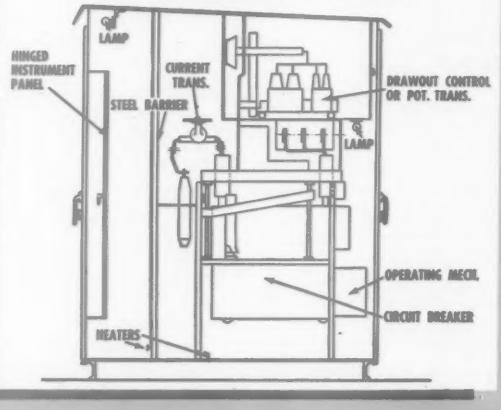
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